Advanced Propulsion Engine Assessment based on a Cermet Reactor

for the

Nuclear Propulsion TIM
October 20-23, 1992

Pratt & Whitney
Randy C. Parsley

25807

PRATT & WHITNEY DESIGN CHOICE BASED ON FUNDAMENTAL PRIORITIES

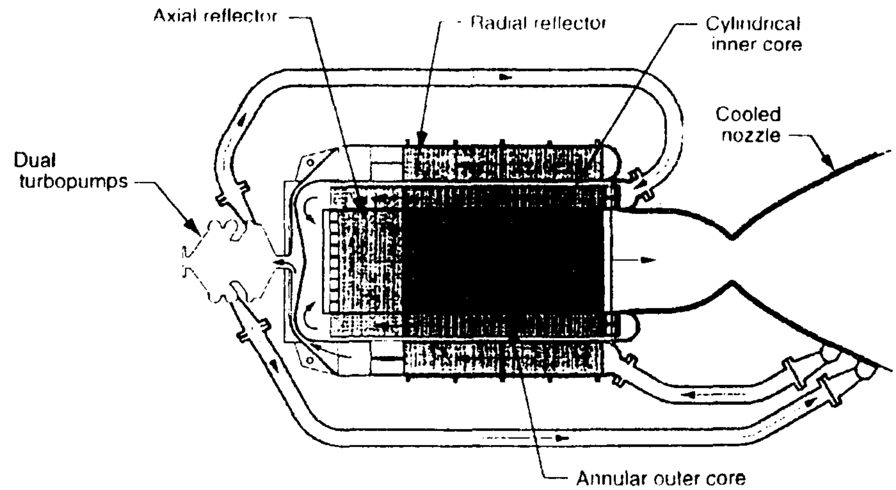
Priority		
1	Safety	Retention of fission products Robust design/simple operation Emergency operation
2	Reliability	Design life = 4X operational Fundamental material compatibility Positive coolant flow management Retention of fuel/stoichiometry Low developement risk
3	Cost	Ground qualification Exploration architecture
4	Performance	High thrust–to–weight High specific impulse

PRATT & WHITNEY XNR2000 CERMET NTRE 25809

Pratt & Whitney Design Choice Based on Fundamental Priorities

A preferred Pratt & Whitney conceptual Nuclear Thermal Rocket Engine, NTRE, has been designed based on the fundamental NASA priorities of safety, reliability, cost, and performance. The basic philosophy underlying the design of the XNR2000 is the utilization of the most reliable form of ultrahigh temperature nuclear fuel and development of a core configuration which is optimized for uniform power distribution, operational flexibility, power maneuverability, weight, and robustness. The P&W NTRE system employs a fast spectrum, cermet fueled reactor configured in an expander cycle to ensure maximum operational safety. The cermet fuel form provides retention of fuel and fission products as well as high strength for a simplified structural design and tolerance to power and temperature cycling. System reliability has been addressed by the use of cermet based fuels, moderate reactor temperatures, and a two-pass reactor flowpath. The cermet, refractory metal fuels provide fundamental material compatibility in the expected operating environment as well as retention of fuel and stoichiometry. The two-pass reactor has been designed to a 4X life requirement and provides positive coolant flow management. A baseline 25,000 lb thrust level is used to minimize ground qualification costs and maximize exploration mission applicability. Finally, the P&W NTRE has been designed to provide high specific impulse at a high thrust-to-weight level.

XNR2000 SYSTEM CONFIGURED AS AN EXPANDER CYCLE



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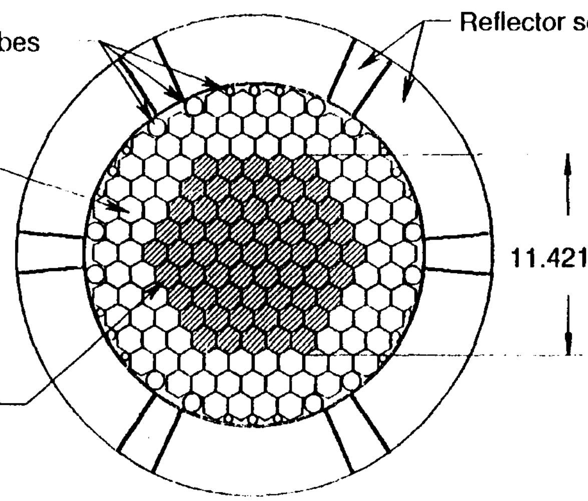
XNR2000 System Configured As An Expander Cycle

The expander cycle was selected for the proven reliability robustness and high efficiency to meet NASA requirements The XNR2000 expander cycle rocket engine uses heat pick-up in the nozzle, chamber, reflector regions, and regenerative cooling of the pressure vessel and upper plenum structure to drive the pumping system and deliver hydrogen to the lower plenum of the reactor core The reactor heats the hydrogen in a two-pass flow configuration and delivers the hydrogen propellant to the nozzle chamber before expansion through a 200 area ratio nozzle. The reactor is comprised of an outer annulus core of 90 Mo-UO2 prismatic fuel elements and an inner cylindrical core of 61 W-UO2 prismatic fuel elements An upper reflector, integral with the fuel elements, is used to provide axial neutron reflection and is comprised of BeO An outer annulus of Be surrounds the reactor and serves as the radial reflector.

The baseline XNR2000 operates at propellant chamber temperature at 2670 K and chamber pressure of 766 psi to deliver 25,000 lbs thrust at a specific impulse of 900 seconds

REACTOR CONFIGURED FROM PRISMATIC FUEL ELEMENTS



PRATT & WHITNEY XNR2000 CERMET NTRE

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XNR2000 Reactor Is Configured From Prismatic Fuel Elements

A medial plane radial cross-section of the XNR2000 NTRE is shown. Looking down at the engine, hydrogen enters the outer annular ring of fuel elements (unshaded) flows up and is then directed through the inner cylinder of fuel elements (shaded) and flows down. The cross section displays the baseline control approach selected for the XNR2000. One possible option for providing redundant reactor shutdown control would be the insertion of Re rods inside the radial support tubes shown in the medial plane cross-section. The rods could be included in the design to prevent inadvertent reactor excursions during transportation, pre-launch, or booster transfer. The Re rods would provide an independent back-up safety mechanism but would not be used for reactor control.

CERMET FUELS WERE PURSUED FOR BOTH PROPULSION AND POWER

Early cermet failures are most remembered not later material successes

Program refocus to power applications reinforce low temperature bias

Successful demonstrations
- 10,000 hrs at 1,950k (in reactor)
- 1,000 hrs at 2,278k
- 3 hrs at 3,178k
- Transients to 2,879k at 10,000k/sec (in reactor)
- 37 hole element fabrication

PRATT & WHITNEY XNR2000 CERMET NTRE 25012

Cermet Fuels were Pursued For Both Propulsion and Power

The basic design philosophy used in the development of the XNR2000 was to employ the most reliable form of ultrahigh temperature nuclear fuel. The approach used to accomplish this goal was to make use of the extensive data and lessons learned in the ROVER/NERVA Nuclear Fuel and Reactor System Development Program, Argonne National Laboratory Nuclear Rocket Program, and the General Electric Advanced Nuclear Propulsion Project 710 Program. A summary of results of cermet fuel development programs of 1960's and 60's is published in two sets of reports: ANL-7236, (1968) "Nuclear Rocket Program", Terminal Report, GEMP-600, (1973), "7.0 High Temperature Gas Reactor Program Summary Report", Vols. I-VI.

P&W INTERNAL STUDIES IDENTIFIED CERMET APPROACH AS SUPERIOR

		Chemical stability		
Constituents	T_{melt}	Matrix	Clad	Hydrogen
UO_2	3100k	Solved*	Total	Total
Tungsten	3650k		Total	Total
Tungsten – Re	3400k			Total

Element

Strength	– High	Clad/matrix CET match	– Good
Conductivity	– High	Matrix/fuel CET match	– Good
Ductility (Cold)	– Adequate		
(Hot)	– Good		

*UO_2 stabilized with 6% Gd or Th

PRATT & WHITNEY XNR2000 CERMET NTRE

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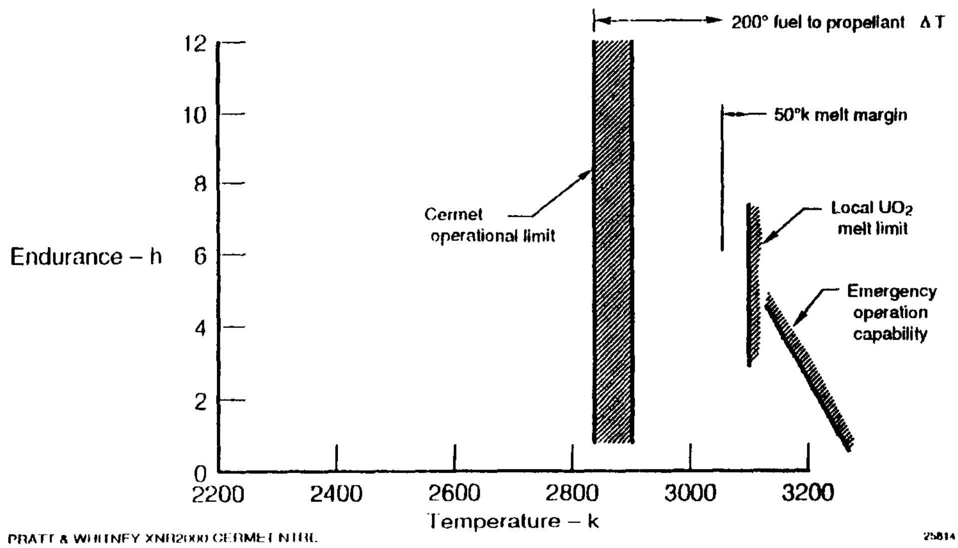
P&W Internal Studies Identified Cermet Approach As Superior

Cermet fuel made of UO2 dispersed in Tungsten or Molybdenum cladded with Mo or W based alloys were tested at high temperature in both nuclear and non-nuclear environments and displayed superior performance in the expected operating environment of an NTRE. Retention of fission products and fuels, thermal shock resistance, hydrogen compatibility, high thermal conductivity, clad/matrix CET compatibility, and high strength are several major advantages of the cermet fuel form.

CERMET OPERATING LIMITS CAN BE ESTABLISHED FROM EXISTING DATA



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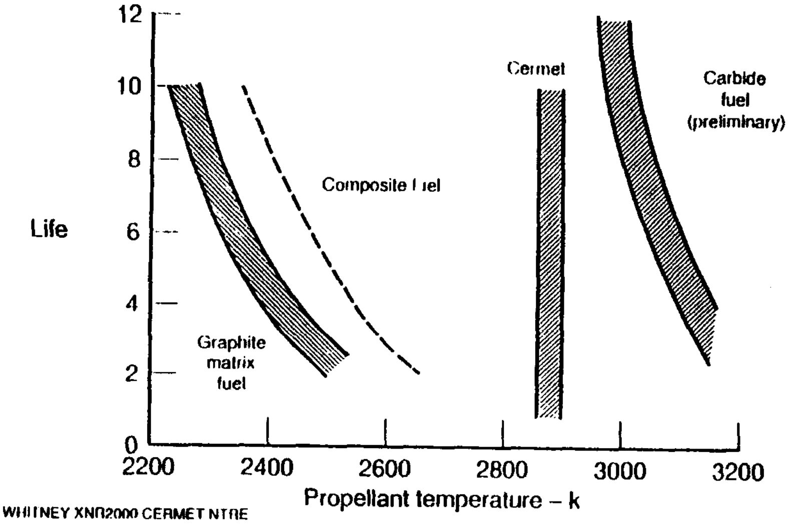
<u>Cermet Operating Limits Can Be Established From Existing Data</u>

A critical review of the cermet fuel development programs was used to establish operating limits for the P&W XNR2000 reactor. The XNR2000 has a temperature margin of 250K using the local UO_2 melt temperature as a conservative upper limit on reactor temperature. The XNR2000 has an endurance on the order of 100's of hours at the selected operating temperature.

CERMET FUEL SHOULD ALWAYS BE INCLUDED ON THIS CURVE



PRATT & WHITNEY XNR2000 CERMET NTRE

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<u>Cermet Fuel Should Always Be Included On This Curve</u>

The predicted endurance of carbon based and cermet based fuels is shown as a function of propellant exit temperature. As shown in the Figure, the endurance of cermet fuels is independent of operating temperature up to the melt temperature of the fuel. However, the endurance of carbon based fuels is a function of propellant temperature because of stoichiometry changes due to chemical diffusion of carbon based fuels in a hot hydrogen environment. A change in the mechanical, thermal, and neutronic characteristics at Carbon based fuels decreases the fuel endurance with increasing operating temperature. The cermet fuels display constant characteristics because there is no fuel/matrix diffusion and the material stoichiometry is constant with temperature.

RESULTS OF NERVA/ROVER RESEARCH REACTOR TESTS WITH TEMPERATURE OVER 2222K

	Time at temperatures over 2222k (sec)	Maximum chamber temperature (k)	Time at max temperature (sec)	Reactivity loss (grams/element)
PHOEBUS-1A, EPIV (22 June 1966)	651	2367	5	?
PHOEBUS-1B (23 Feb 1967)	400	2292	5	13.7
PEWEE-1 (Dec 1968)	–	2555 (fuel exit temp)	2400	20
NF-1 (June 1972)	–	2444 (fuel exit temp)	6528	13.7

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<u>Results of NERVA/ROVER Research Reactor Tests With Temperature Over 2222</u>

A short summary of often quoted NERVA/ROVER test results. It should be noted that while time at temperatures over 2222 is high, and most often quoted, the time at maximum temperatures is often quite low. Additionally, fuel temperatures are often quoted rather than the lower hydrogen temperatures, adding to the confusion. Reactivity loss was proven to be a major concern in the NERVA/ROVER Program and could significantly increase the cost or even prohibit ground qualification.

ORIGINAL PAGE IS
OF POOR QUALITY

RESULTS OF NERVA/ROVER DEVELOPMENT REACTOR TESTS WITH TEMPERATURE OVER 2222K

	Time at temp over 2222k (sec)	Max temp (k)	Time at max temp (sec)	Reactivity loss (cents)
NRX–A3 (23 April 1965)	5	2244	3	22.3
NRX/EST, EPIII (2 March 1966)	75	2292	5	2.5
NRX/EST, EPIV (16 March 1966)	110	2264	5	46.7
NRX/EST, EPIVA (25 March 1966)	816	2264	450	282.4
NRX–A5, EPIII (8 June 1966)	473	2286	7	22.5
NRX–A5, EPIV (23 June 1966)	873	2333	7	212.3
NRX–A6, EPIIIA (15 Dec 1967)	3764	2405	10	70
XE–PRIME, EP5 (March 1969)	10	2278	5	–

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PRATT & WHITNEY XNR2000 DESIGN TEAM

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Pratt & Whitney

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Gerald Feller (Nuclear)
Mike Malone (Materials)
Paul Harris (Materials consultant)

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Steve Scoles (P.I.)
Russ Jensen (Materials)
James Rhodes (Nuclear)

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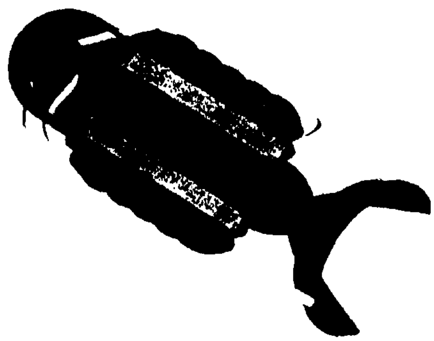
XNR2000 CONCEPT CONFIGURED TO ADDRESS P&W PRIORITIES



- Fast spectrum CERMET
- Dual pass reactor
- Robust and safe

PRATT & WHITNEY XNR2000 CERMET NTRE

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XNR2000 Concept Configured To Address P&W Priorities

A conceptual nuclear thermal rocket (NTR), the XNR2000, has been developed for manned space exploration missions. The discriminating features of the XNR2000 that provide attractive attributes are the use of Cermet fuel, a dual-pass reactor flowpath, and a simple robust cycle. An XNR2000 system description, reactor thermal hydraulic summary, and throttling, operating temperature, and thrust size effects will be presented. This package presents the summary of a 6 month NASA funded study to develop and assess concept feasibility, thrust level range implications, and manned mission impacts of an NTR system based on a prismatic Cermet reactor.

XNR2000 CONFIGURED TO MEET NASA REQUIREMENTS

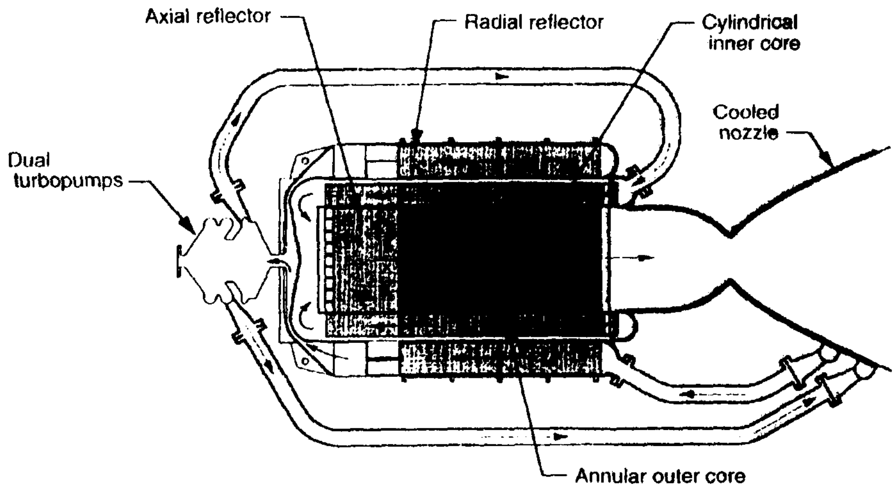
- I_{sp} > 850 sec (at 200 area ratio)
- T/W > 4
- Throttling 25% at rated temperature
- Single burn duration 60 min (max)
- Engine life > 270 min at rated thrust
- Remain subcritical upon impact and immersion
- ALARA fission product release
- Dual turbopump arrangement
- 25k, 50k & 75k Thrust size

PRATT & WHITNEY XNR2000 GEOMETRY NTRE 25574

XNR2000 Configured To Meet NASA Requirements

The XNR2000 Nuclear Thermal Rocket Engine, NTRE, was configured to meet or exceed the performance requirements of a man-rated NTR System. The propulsion requirements listed are described in detail in the "Nuclear Thermal Rocket Engine Requirements" document, version 3 February 10, 1992. The baseline thrust size was set at 25,000 lb, and thrust size effects were determined for engines of 50,000 and 75,000 lb. of thrust. Safety and reliability are key NTRE propulsion requirements for the manned-mission Space exploration applications and were considered foremost in the conceptual design of the XNR2000. The reactor fuel and spectrum selection was specifically dictated by the ALARA fission product release and reactor subcriticality requirements.

XNR2000 SYSTEM CONFIGURED AS AN EXPANDER CYCLE



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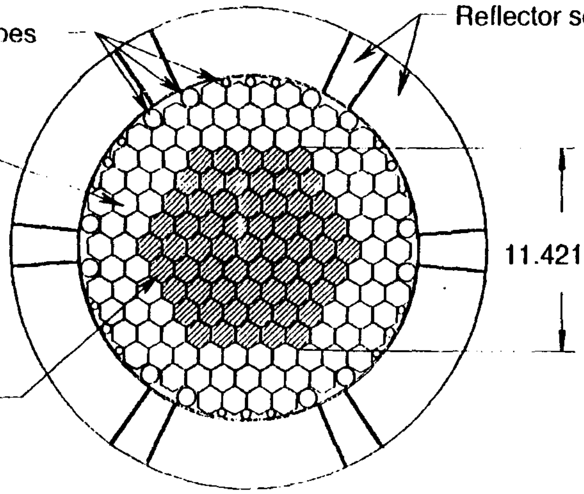

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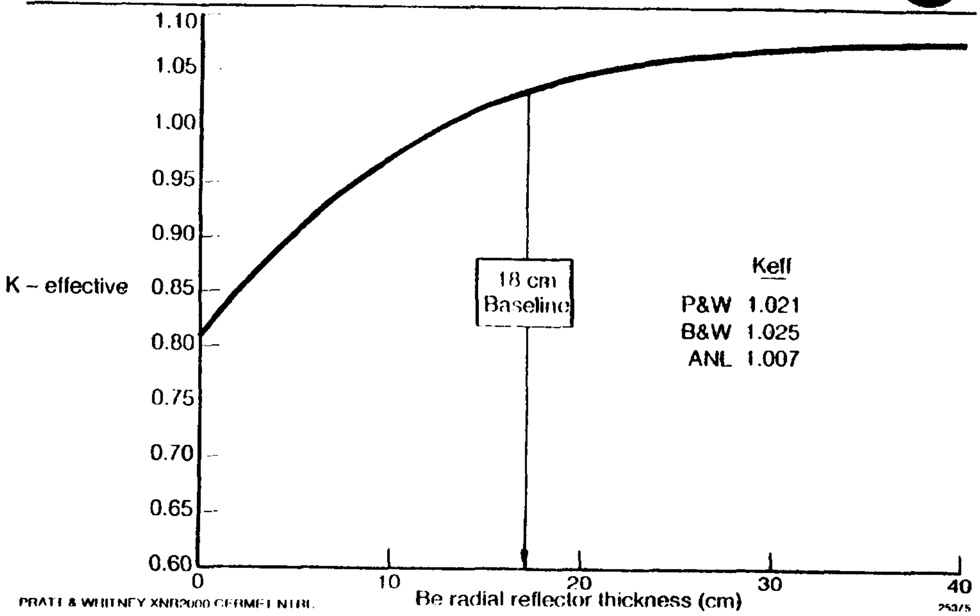
CRITICALITY CONFIRMED BY B&W AND ANL

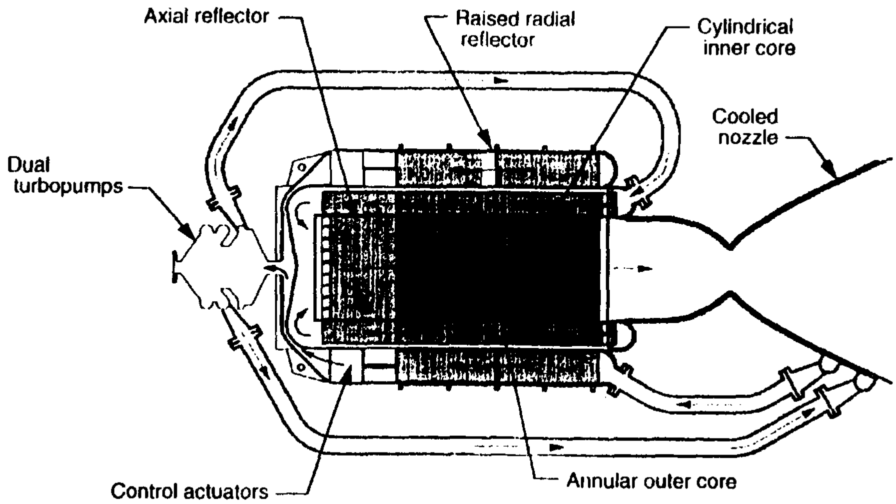


<u>XNR2000 Criticality Confirmed by B&W and ANL</u>

The calculated values of system Keff by Pratt & Whitney agree with calculations of Keff conducted independently by Babcock & Wilcox (B&W) and Argonne National Lab (ANL). Pratt & Whitney used both a 16 energy group combine/venture diffusion code analysis and MCNP statistical code analysis to calculate Keff and ANL used MCNP statistical code analysis procedures to calculate Keff.

The plot of Be radial reflector thickness vs. Keff for the baseline configuration, displays the large worth of reactivity for the reflector under approximately 30 cm. This curve indicates that the system can be controlled with neutron reflection. The baseline system employs an 18 cm radial Be reflector and a 20 cm BeO axial reflector.

XNR2000 SYSTEM CAN BE CONTROLLED BY RAISING REFLECTOR SECTION



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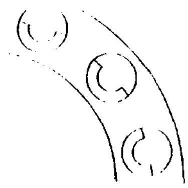
<u>XNR2000 System Can Be Controlled By Raising Reflector Sections</u>

The baseline control approach was designed to provide robust reactor control with minimum complexity and weight. The control of the reactor is accomplished by varying the neutron-leakage rate by means of 10{SYMBOL 176 \f "Symbol"} moveable annular segments of the radial reflector. The lower half of each segment is stationary while the upper half translates axially to provide reactor control through the "opening of windows". Nuclear control is provided by 1 bank of 3 segments while fast-shutdown capability is provided by the other, independent, bank of 3 segments. The selected control approach provides the most reactivity worth for the selected reflector size, thus maximizing thrust to weight. The reflector segments are driven by pneumatic piston-type drive mechanisms which provide linear actuation.

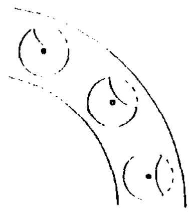
ALTERNATE CONTROL OPTIONS ARE VIABLE



Conventional drums

Estimated worth

$\frac{\Delta K}{K}\Big|_{TOTAL} = -4\%$



Rotating windows

$\frac{\Delta K}{K}\Big|_{TOTAL} = -5\%$

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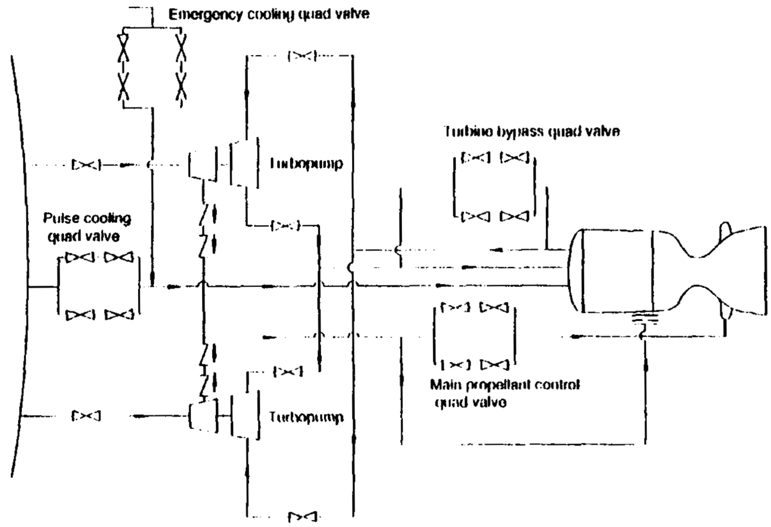
Alternate Control Options Are Viable

The baseline control approach was selected for simplicity and reduced weight, however other control options are viable for the XNR2000. Shown here are two such approaches with a preliminary calculation of reactivity worth. Contemporary control drums consisting of Be with partial segments of Re poison material could provide sufficient negative reactivity insertion for control. Additionally, the use of rotating drums with segments of void could be used to provide control through neutron leakage in a rotating drum configuration. The optimum control of the XNR2000 could be achieved through the combination of any of the three approaches presented, providing nuclear control with maximum redundancy.

BASELINE PROPELLANT SYSTEM CONFIGURED WITH DUAL TURBOPUMPS



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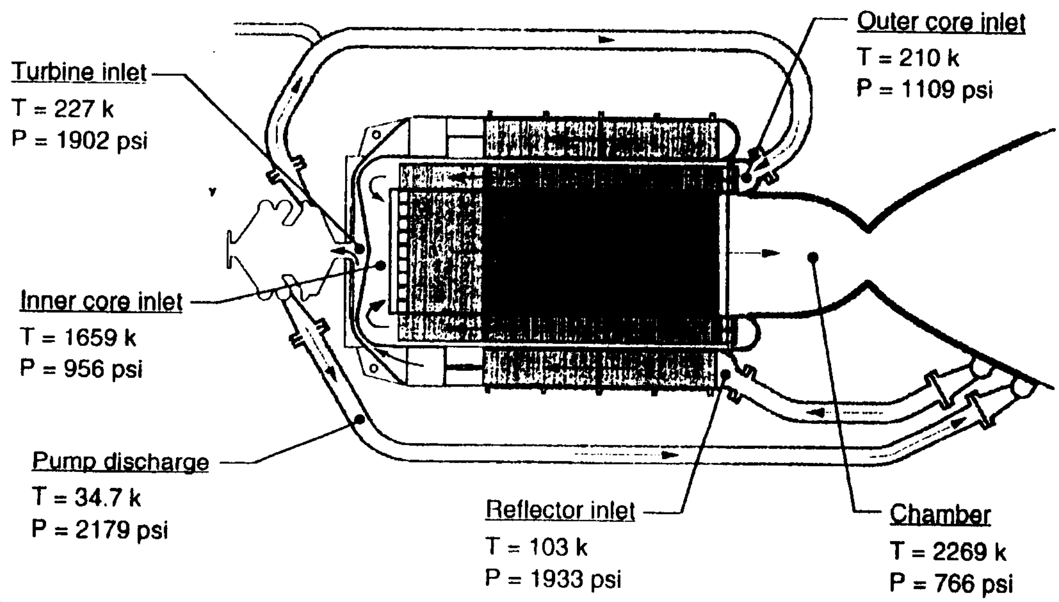
Baseline Propellant System Configured With Dual Turbopumps

A flow schematic of the baseline engine is shown. Dual turbopumps are employed with quad valve arrangements to maximize system reliability. Each turbopump delivers 50% of the total reactor flow and can be isolated with block valves in case of a pump out condition. The quad valves consist of 2 block valves followed by 2 control valves arranged in parallel. The 2 pumps pressurize and deliver hydrogen to the nozzle coolant tubes and reflector. The heated hydrogen is then expanded through the turbine and delivered to the reactor. Preliminary investigations indicate that the system could operate at 75% thrust during an engine out scenario. After engine operation pulse cooling of the reactor is provided with pressurized or tank head hydrogen through the pulse cooling quad-valve to remove residual heat generation. An emergency pressurized hydrogen tank would provide pressurized hydrogen to the reactor under a 2 pump out, reactor critical condition.

XNR2000 EXPANDER CYCLE IS ROBUST AND EFFICIENT



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CERMET ADVANTAGES ESTABLISHED IN GE710/ANL PROGRAMS

Characteristic	Payoff
Demonstrated fabrication	Reduced risk
Fuel matrix / cladding / hydrogen compatibility	Life, FFP retention
High strength and conductivity	Thrust–to–weight, robustness
High temperature operating capability	Specific impulse

Characteristics confirmed by B&W

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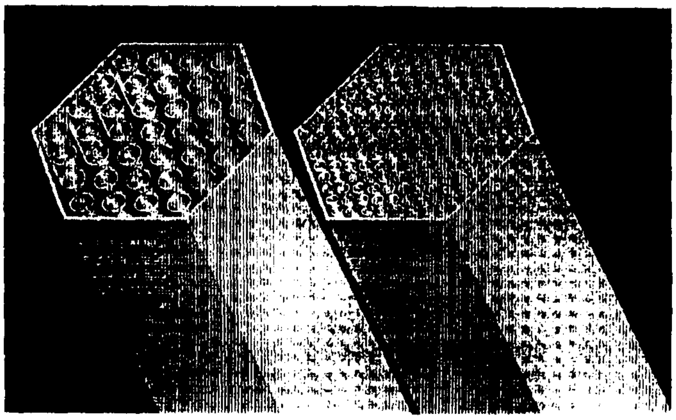
<u>Cermet Advantages Established In Ge710/ANL Programs</u>

The XNR2000 builds upon the experience and database of Cermet fuels obtained in the GE710 and ANL programs. The fast spectrum Cermet fuel form was selected to meet the engine requirements of ALARA fuel and fission product release, multiple restart capability and subcriticality under credible accident scenarios. During the GE710/ANL programs the Cermet fuel form displayed tolerance to excessive temperature/power ramps due to the high strength and conductivity of the refractory metal matrix. Additionally Cermet fuel display complete compatibility in the expected hot H2 operating environment as well as cladding and fuel matrix CTE compatibility. Finally the XNR2000 is based upon a fuel form that was successfully fabricated and tested.

PROPOSED FUEL ELEMENT CONFIGURATION HAS BEEN UPDATED



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Proposed Fuel Element Configuration Has Been Updated

Subsequent to the Mid-term evaluation of this study, the baseline concept has been upgraded to incorporate a fuel element based on demonstrated technologies. The baseline fuel form incorporates 37 large diameter coolant channels compared to 169 small diameter coolant channels initially considered for this concept. The max. operating fuel temperature was maintained at 2880K, well within the experimental database. Because of the increased thermal path, fuel centerline to coolant channel surface, between the fuel forms the reactor exit propellant temperature was reduced to 2669K from 2850K. This chamber temperature provides an Isp level of 900 seconds with life greatly in excess of the NASA requirements.

BASELINE FUEL ELEMENT WITHIN FABRICATION EXPERIENCE

Parameter	Inner core element	Outer core element
Number of fuel elements	61	90
Distance across flats [a]	1.40 in.	1.40 in.
Diameter of flow hole [D]	.14 in.	.14 in.
Flow hole pitch	0.215 in.	0.215 in.
Thickness of flow tube [t]	0.007 in.	0.007 in.
Thickness of external can [W]	0.02 in.	0.02 in.
Number of flow holes	37	37
Fuel matrix materials	UO_2-W-Gd_2O_3	UO_2-Mo-Gd_2O_3
Metal in fuel matrix	W	Mo
Fuel can materials	W-Re	Mo-Re
Flow tube material	W	Mo
Uranium enrichment (wt%)	93.0	93.0
Vol. fraction of UO_2 in fuel matrix	0.6	0.0
Vol. fraction of Gd_2O_3 in fuel matrix	0.06	0.06
Vol. fraction of metal in fuel matrix	0.34	0.34
Vol. fraction of Re in external can	0.25	0.50
Vol. fraction of metal in external can	0.75	0.50
Flow hole void fraction	0.3425	0.3425
Total core power (MW)	510	
Total core volume (L)	101.1	
Active core volume (L)	66.47	
Heat transfer area/total flow area	1447.3	
Fuel element height	24 in.	
Radial reflector (Be) thickness	7.1 in.	
Axial top reflector (BeO) thickness	7.87 in.	
W sheet thickness on inner core bottom	1 in.	

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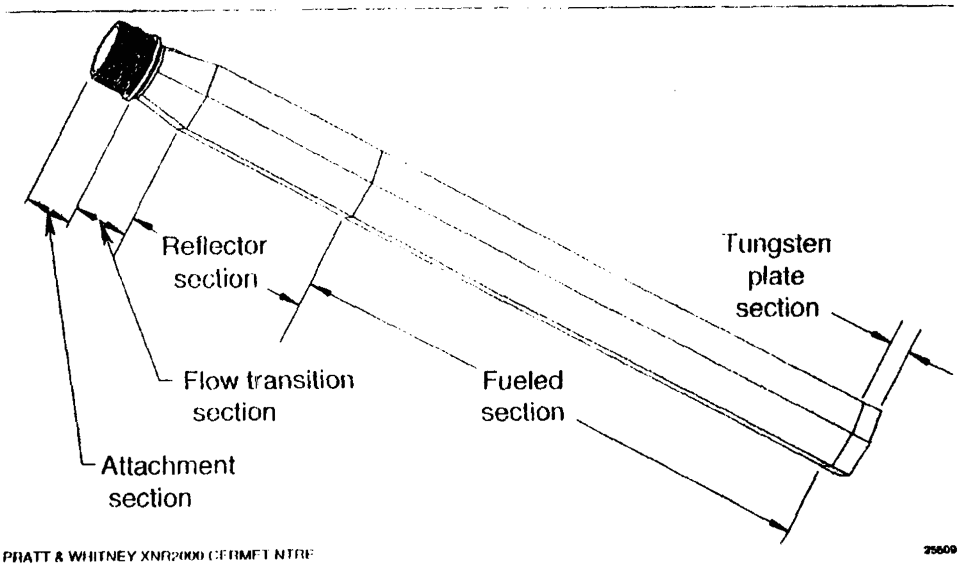
Baseline Fuel Elements Within Fabrication Experience

The selected baseline prismatic Cermet fuel element is based on demonstrated technology. The outer core fuel elements consist of 60 vol%-UO2-Mo fuel matrix contained within Mo-50% Re external core. The inner core fuel elements consists of 60 vol% UO2-W fuel matrix contained within a W-26% Re external core. Rhenium has been incorporated into the external can designs to decrease the ductible-to-brittle transition temperature and provide adequate ductility for cyclic life requirements. All fuel elements have a hexagonal cross section with a 1.4 inch flat-to-flat distance and contain 37 coolant channels .14 inch in diameter.

The coolant channels are coated with the refractory metal contained within the matrix. UO2 is stabilized with 6% GdO3 in both cores to provide fuel stabilization and prevent fuel migration. Fuels elements of this type were successfully fabricated and tested in the early 70's with technology that can be easily recovered and enhanced with a core recent fabricated techniques.

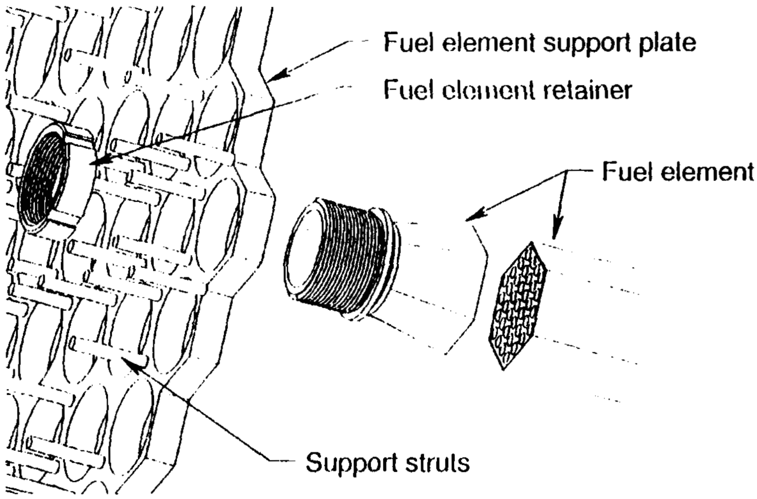
AXIAL REFLECTORS INTERGRAL WITH FUEL ELEMENTS



Axial Reflectors Integral With Fuel Elements

The baseline prismatic Cermet fuel element for the inner core is shown. The axial BeO reflector section is integral with the fuel element, contained within the same structural support external can. The attachment section is used in a support system. The loaded section of the fuel element is 24 inches (61 cm.) in length and the axial reflector is 7.9 inches (20 cm.).

HIGH STRENGTH FUEL ELEMENTS ALLOW SIMPLIFIED CORE SUPPORT



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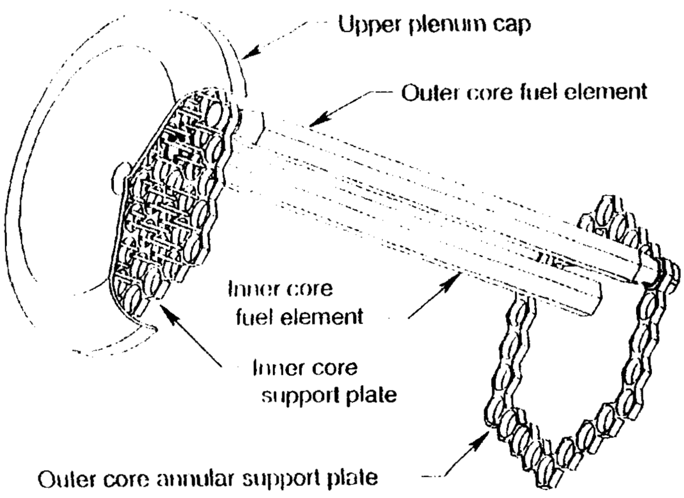
<u>High Strength Fuel Elements Allow Simplified Core Support</u>

The XNR2000 is not susceptible to material neutronic poisoning because of the fast spectrum operation of the reactor. Therefore, high strength refractory metals can be used in both the fuel matrix and support structure to eliminate the need for tie rods. The baseline conceptual core support design is shown below. The fuel elements are simply supported, at the hydrogen inlet end, to the support plate with a threaded fuel element retainer. The fuel elements are placed in tension because of propellant friction and accelerational pressure drop which acts to increase the natural frequency of the fuel element and reduce the propensity for flow induced vibration.

CONCEPTUAL CORE ASSEMBLY APPROACH



PRATT & WHITNEY XNR2000 CERMET NTR

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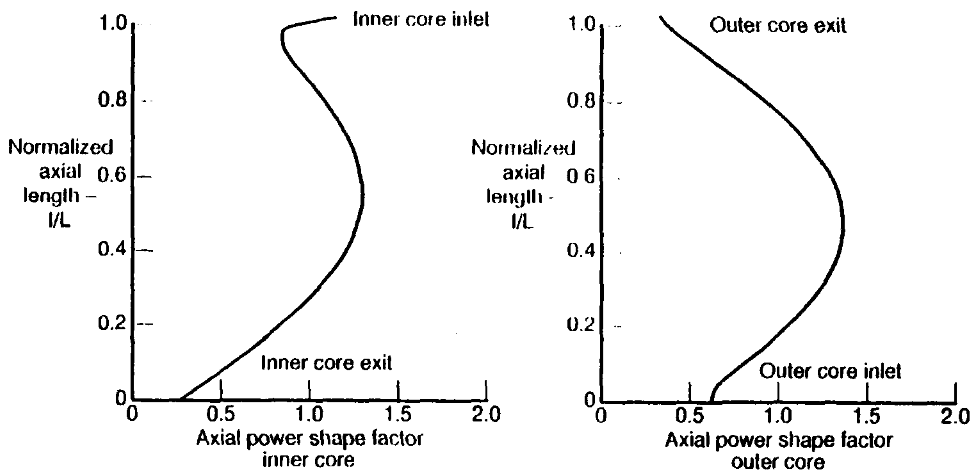
Conceptual Core Assembly Approach

Shown below is the conceptual inner and outer core fuel element support approach. The outer core elements are simply supported at their cold end by a lower grid plate which is bolted to the inner pressure vessel. The outer core elements are allowed to translate through the upper support plate to allow for axial thermal growth. The inner core fuel elements are rigidly attached at their cold end by the upper grid plate. The upper grid support plate is bolted to the inner pressure vessel with additional support provided by axial struts attached to the upper plenum head.

A tungsten shroud will be used between the two cores to act as a thermal baffle and provide a compressive spring preload against radial inner core fuel element growth. The tungsten shroud will conform to the hexagonal cross section of the fuel elements and extend from the upper support plate to the nozzle chamber. The shroud will transition from a hexagonal cross-section to a circular cross-section in the chamber region. The nozzle coolant tubes will run behind this shroud in a circular pattern to provide chamber cooling.

AXIAL POWER DISTRIBUTION PREDICTED FOR THERMAL HYRAULIC ANALYSIS



PRATT & WHITNEY XNR2000 CERMET NTRE

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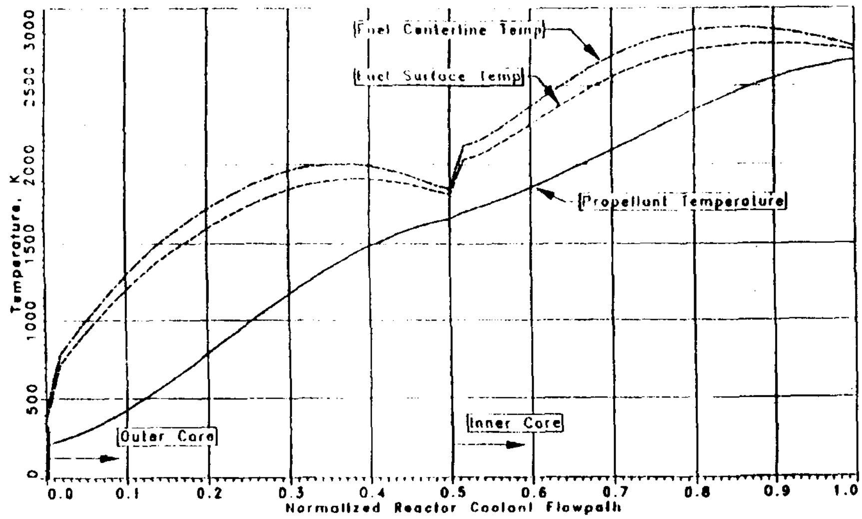
__Axial Power Distribution Predicted For Thermal Hydraulic Analysis__

The predicted average axial power shape factors for the inner and outer cores are shown. These power profiles were determined using the 3-D diffusion theory code, BOLD VENTURE, and benchmarked with MCNP statistical codes. The inner core power profile decreases at the exit of the reactor where the temperatures are the highest. The sharp increase in power at the inner core inlet is caused by the BeO axial reflector located directly above the reactor. These power profiles were determined to conduct a coupled neutronic/thermal hydraulic analysis of the XNR2000 reactor.

PEAK FUEL TEMPERATURE IS MAINTAINED BELOW 2900K



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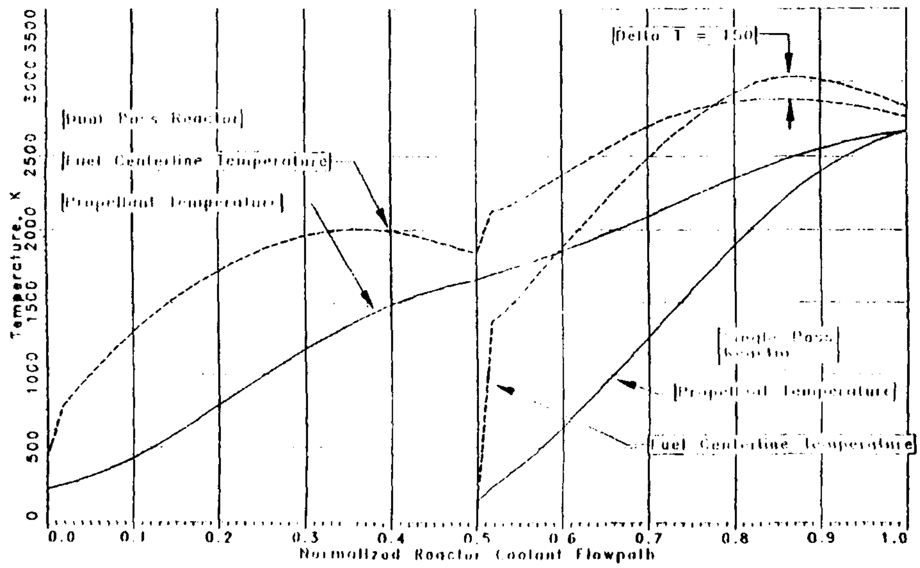
<u>Peak Fuel Temperature Is Maintained Below 2900k</u>

The calculated propellant, fuel surface, and fuel centerline temperature distribution within the XNR2000 reactor at full power operating condition is shown. The temperature distribution is plotted against the normalized reactor coolant flowpath location, where 0.0 corresponds to the outer core inlet and 1.0 corresponds to the inner core exit. This temperature distribution was calculated using a one-dimensional coupled thermal hydraulic/neutronic analysis benchmarked with detailed 3-dimensional computational fluid dynamics, CFD, procedures. As shown in the figure, the maximum fuel temperature reached in the inner core is 2880K and 2000K in the inner core. These maximum fuel temperatures were selected for design operation to exceed life requirements and assure positive fission product and fuel retention. A propellant chamber temperature of 2669k was calculated using a 2880k max fuel temperature as the upper limit.

DUAL PASS REDUCES FUEL TEMPERATURES AND AXIAL THERMAL GRADIENTS



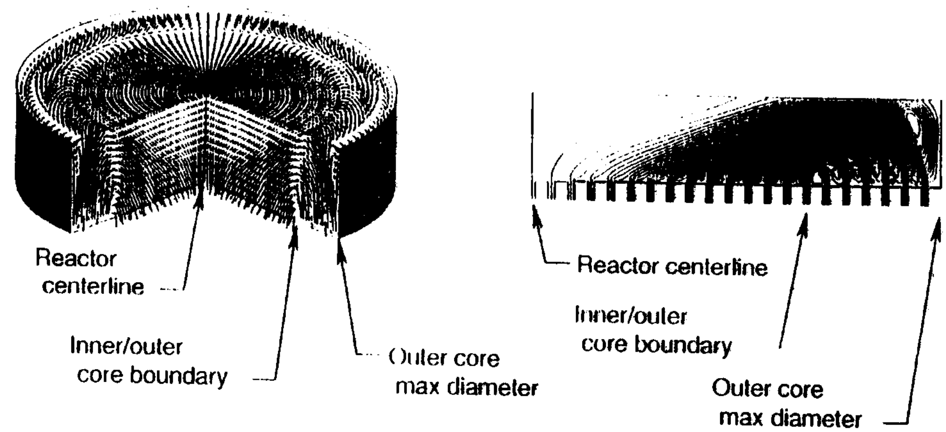
Dual Pass Reduces Fuel Temperatures And Axial Thermal Gradients

The figure displays several benefits of the dual pass reactor flow configuration. The dual pass provides reduced axial thermal gradients in the fuel elements. As shown in the figure, a temperature gradient of 1500K appears across the outer core elements and a gradient of 1100K appears across the inner core elements, in the dual pass configuration. However, in a single pass configuration a temperature gradient of 2600K appears across each fuel element. The dual pass flowpath reduces the axial thermal gradients of the elements by approximately 50%, reducing thermal stresses and increasing fuel tolerance to power cycling. Additionally, in a dual pass reactor max fuel temperatures are reduced by approximately 150{SYMBOL 170 \f "Symbol"}K for equal propellant chamber temperatures and power density. This is a result of increased heat flux and decreased convective heat transfer in the single pass configuration, for equivalent reactor power density levels.

C-3

PRELIMINARY UPPER PLENUM CFD RESULTS

Stream function of jet–induced flow



PRATT & WHITNEY XNR2000 CERMET NTRE

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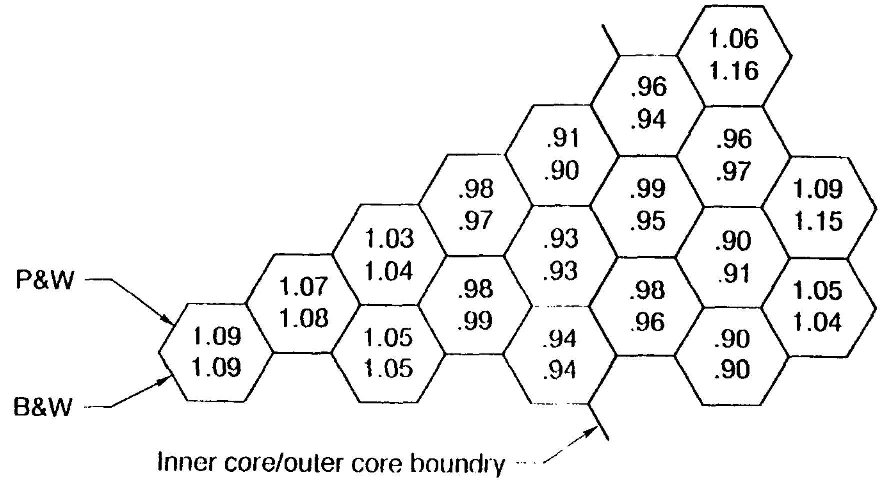
Preliminary Upper Plenum CFD Results

A Computational Fluid Dynamic (CFD) analysis was conducted to evaluate the flow distribution and heat transfer in the XNR2000 reactor coolant channels and upper plenum region. The predicted flow distribution in the upper plenum is shown below. The results of the CFD analysis were used in the upper plenum design and to benchmark the one dimensional thermal hydraulic reactor analyses.

XNR2000 RADIAL POWER DISTRIBUTION CONFIRMED BY B&W



PRATT & WHITNEY XNR2000 CERMET NTRE

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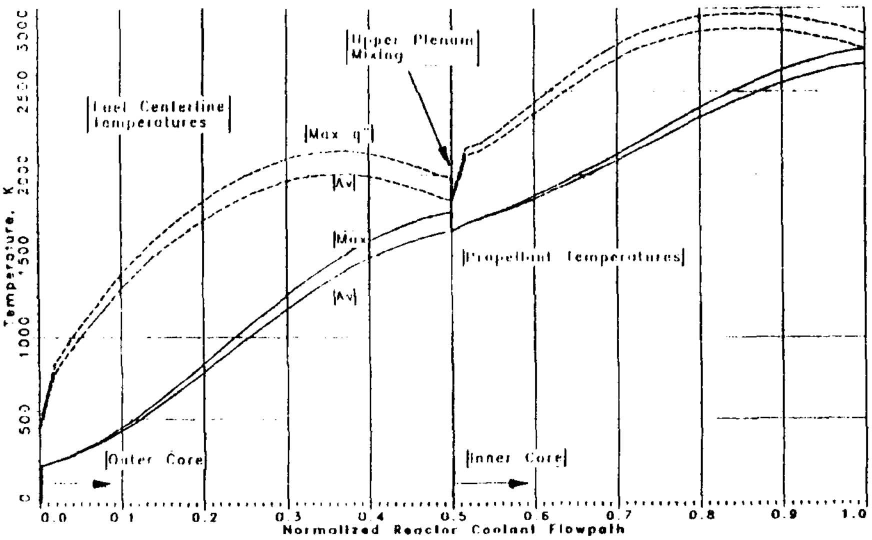
<u>XNR2000 Radial Power Distribution Confirmed By B&W</u>

The calculated rodwise normalized power distribution within a segment of symmetry of the XNR2000 reactor is shown. Close agreement between the calculated results of Pratt & Whitney and Babcock & Wilcox is shown. As expected, the maximum power peak of the inner core appears at the center of the reactor while the power peak of the outer core appears closest to the radial Be reflector. These results were used in the thermal hydraulic analysis to conduct power/flow matching evaluations. As shown in the diagram the maximum peak-to-average fuel element power level was calculated to be 1.09 for both the inner and outer cores.

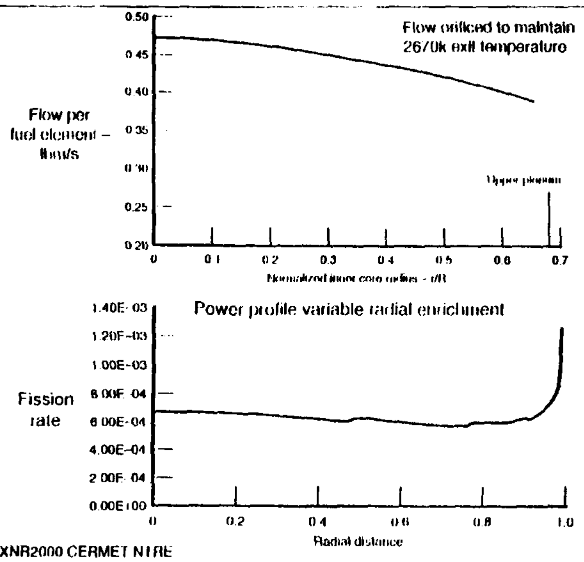
UPPER PLENUM MIXING FLATTENS RADIAL POWER PROFILE



<u>Upper Plenum Mixing Flattens Radial Power Profile</u>

The calculated propellant and fuel centerline temperature distribution within the XNR2000 reactor for fuel elements having the average and maximum peak-to-average power levels is shown. The calculated radial power distribution shown on the previous chart, was used to conduct a thermal hydraulic evaluation of the reactor to determine the impact of peak power levels on reactor temperatures. The analysis displays the upper plenum mixing advantage of the dual pass core. Any outer core hot channeling effect due to uneven power profiles is removed from the inner core because of thermal momentum fluid mixing in the upper plenum. This mixing reduces the propellant and therefore reactor temperatures in the inner core. The energy and momentum mixing allows for up to 15% power peaking in the outer core without orificing. As shown, the maximum temperature is approximately 2950k for the inner core and 2200 for the outer core in the fuel elements having the maximum power levels. This analysis displays the worst case scenario in which no attempt is made to flatten the power profile.

PROFILE CAN BE ADDRESSED BY VARIABLE ENRICHMENT OR ORIFICING



PRATT & WHITNEY XNR2000 CERMET NTRE 25387

Profile Can Be Addressed By Variable Enrichment Or Orificing

Two methods of addressing the power profile were evaluated and both were found to be acceptable. The first approach of handling the variable power profile was orificing the propellant flow in the inner core to provide a constant 2670K reactor exit temperature. By orificing the flow at the inlet of each fuel element the proper flow rate can be delivered to each element depending on the element power level. Shown below is the fuel element flowrate, as a function of inner core radius, required to provide a constant reactor exit temperature.

The second possible approach to flatten the power profile evaluated was variable radial Uranium enrichment. The enrichment within both the inner and outer cores was varied to determine the impact on radial power distribution. As shown in the figure a nearly constant power profile was obtained by varying the enrichment by approximately 4% across the reactor radius.

DUAL PASS CONFIGURATION HAS SIGNIFICANT ADVANTAGES

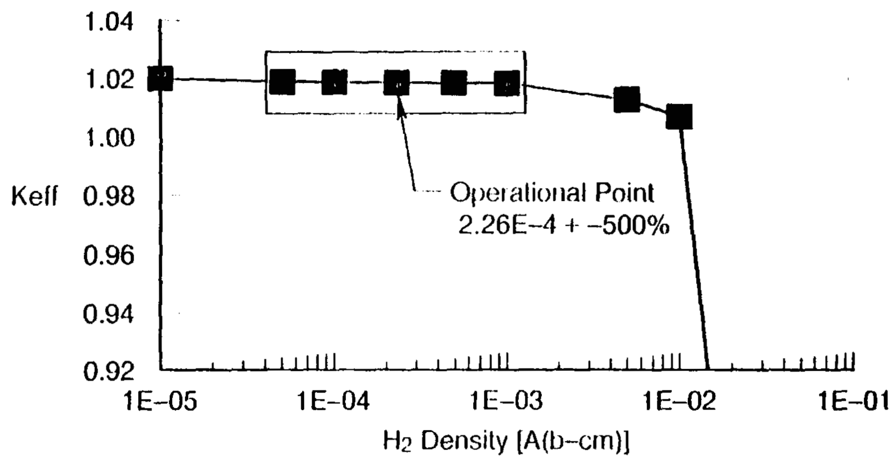
- Flat radial power profile
- Positive flow/power matching
- Upper plenum mixing reduces peak temperature
- High temperature inner core isolation
- Reduced element axial thermal gradient

PRATT & WHITNEY XNR2000 CERMET NTRE 25384

Dual Pass Configuration Has Significant Advantages

The primary attractive features provided by the dual pass reactor core are summarized. A flat radial power profile is provided by the dual-pass reactor due to the averaging of power distributions relative to two distinct regions. Positive flow/power matching is achievable because of the separation of the inner and outer cores. The maximum fuel element power shape factors appear in the outer core region because of the proximity of the radial reflector. However, because the outer core serves as the first pass, the coolest hydrogen propellant passes through the outer core and eliminates fuel temperature concern. Additionally, upper plenum mixing of the hydrogen serves to eliminate the outer core power peaks from the inner core fuel elements. The dual pass configuration isolates the hot inner core fuel elements from the rest of the engine system. This isolation provides material flexibility allowing the use of lighter weight Moly based fuel elements in the outer core and a Be radial reflector which provides the most reactivity worth for the weight. The most obvious benefit of the dual pass core is the reduced axial thermal gradients and consequently thermal stress loads placed on the fuel elements.

COMPLICATIONS OF H_2 MODERATION ELIMINATED DURING STARTUP, SHUTDOWN, AND THROTTLING

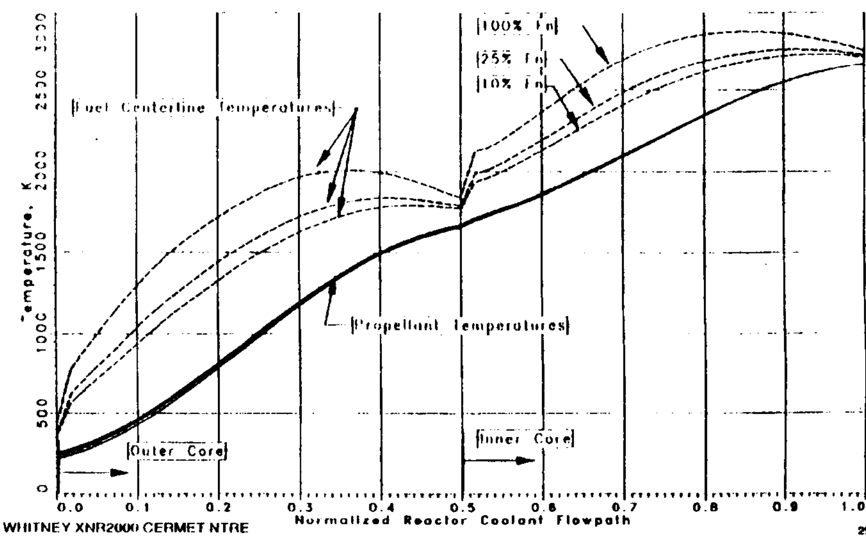


PRATT & WHITNEY XNR2000 CERMET NTRE 25803

Complications Of H2 Moderation Eliminated During Startup, Shutdown, and Throttling

There is no impact of Hydrogen moderation on the fast spectrum XNR2000 reactor. The calculated effect of Hydrogen density on system K_{eff} is shown. The complications of reactivity feedback from the hydrogen propellant and potential for thermal instability is eliminated during transient and steady state operation in the KNR2000.

PEAK FUEL TEMPERATURE DECREASES AT THROTTLED CONDITIONS



PRATT & WHITNEY XNR2000 CERMET NTRE

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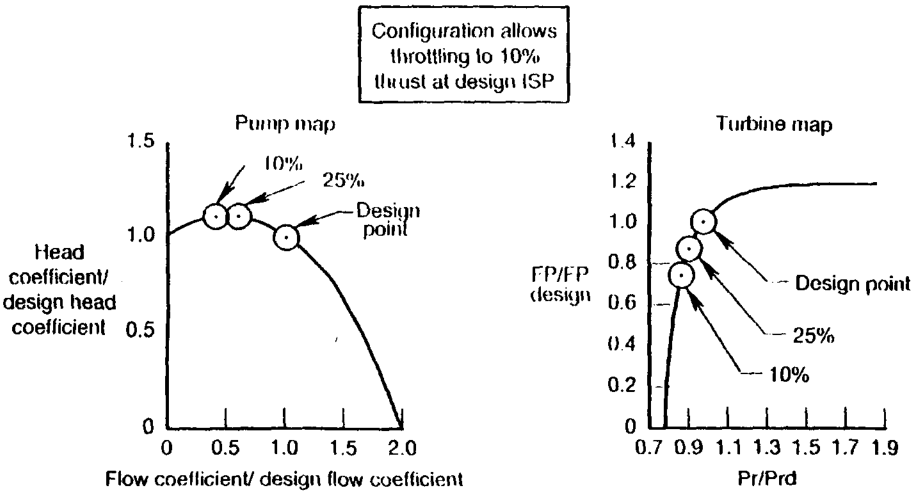
Peak Fuel Temperature Decreases At Throttled Conditions

The calculated propellant and fuel centerline temperatures are shown for the baseline **XNR2000 at full thrust, 25% thrust and 10% thrust throttled conditions.** **As displayed** in the chart the peak fuel temperatures **within the reactor decrease as the engine is throttled.** The reduced reactor **temperatures** result from the reduced power flux required **to deliver the throttled mass flow rate to the design** point temperature **levels.** This quasi steady analysis **was simplified** because of the negligible **effect of H2 moderation on the reactivity** of the core.

STARTUP, SHUTDOWN AND THROTTLING, UNAFFECTED BY H_2 MODERATION



PRATT & WHITNEY XNR2000 CERMET NTRE

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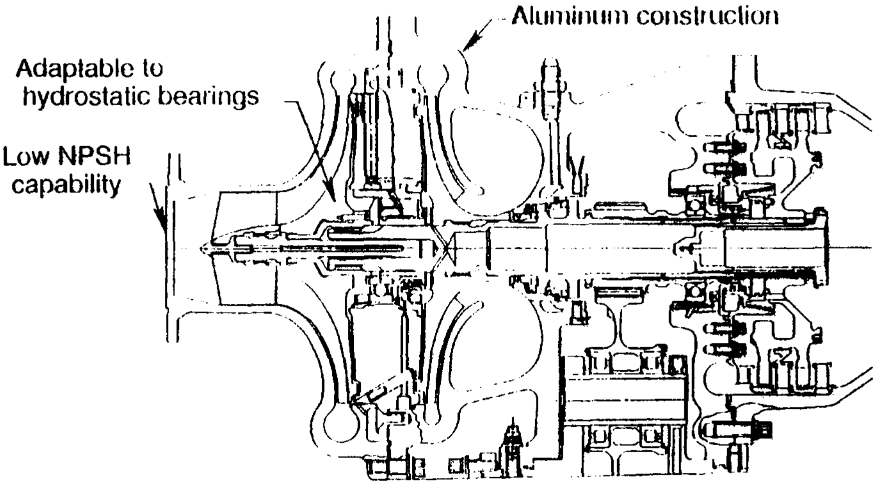
Startup, Shutdown And Throttling, Unaffected By Hydrogen Moderation

The pump and turbine operating map of the XNR2000 is shown for throttled and design point conditions. The RL10 upper stage expander cycle rocket engine turbopump characteristics were assumed in this analysis. This analysis indicates that the configuration allows throttling to at least 10% thrust at design specific impulse

INDIVIDUAL TURBOPUMP REQUIREMENTS ARE SIMILAR TO RL10



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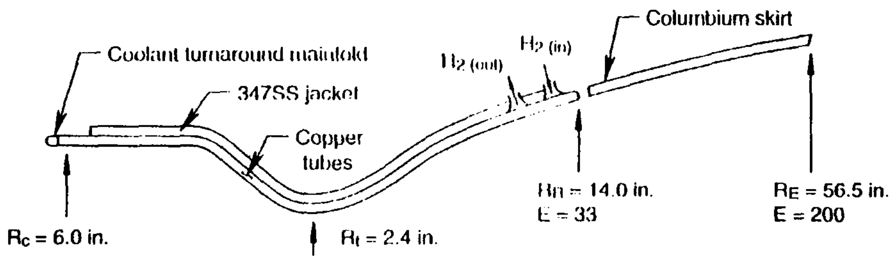
<u>Individual Turbopumps Requirements Are Similar to RL10</u>

Demonstrated characteristics of the RL10 engine turbopumps will be required of turbopumps used in an NTRE for manned space exploration missions. The XNR2000 conceptual design employs a two stage centrifugal pump that is similar in flow rate and head rise to the RL10 turbopump, driven by a turbine operating at cool inlet temperatures. The system requirements call for throttling to at least 25% thrust at rated temperature and operation at low NPSH levels. These requirements are similar to those of the RL10 liquid hydrogen turbopumps. The RL10 turbopumps deliver pressurized hydrogen to the RL10 engine for upper stage applications. This pump has successfully demonstrated zero to low NPSH capability and throttling down to 2% flow. With the incorporation of hydrostatic bearings, operation in a radiation environment can be achieved because of the aluminum construction. For these reasons the characteristics of the RL10 Turbopumps were used in the study of The XNR2000 concept, and that a scaled or derivative version of this proven pump would be employed in the design.

NOZZLE IS ACTIVELY COOLED COPPER WITH AN UNCOOLED SKIRT



Regen section		**Skirt**	
Coolant configuration	Two pass	Coolant configuration	Radiation
Number of tubes	300	Skirt material	Columbium
Tube material	Glidcop	Max heat flux	1 Btu/in^{2}sec
Max heat flux	51 Btu/in^{2}sec	Max skirt temperature	1792K (2766°F)
Max tube temperature	811K (1000°F)		
Pressure drop	225 psi		

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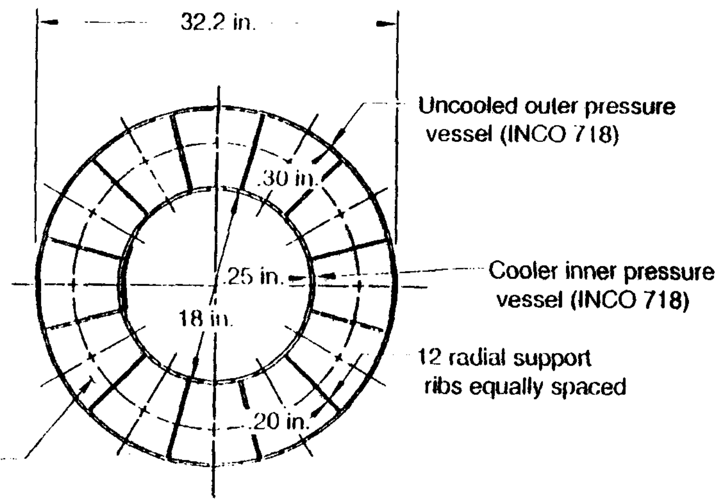
Nozzle Is Actively Cooled Copper With An Uncooled Skirt

The XNR2000 employs a regeneratively cooled chamber and nozzle and radiativly cooled nozzle skirt. The nozzle and chamber is cooled to an area ratio of 33 with 300 copper tubes in a two pass configuration with 30% of the total engine flow. The chamber pressure vessel consists of a 347 Stainless Steel jacket surrounding the copper tubes. The system employs a Colombian nozzle skirt from an area ratio of 33 to 200 which is radiativly cooled.

XN2000 PRESSURE VESSEL IS SIMILAR TO ANL APPROACH



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<u>XNR2000 Pressure Vessel Is Similar To ANL Approach</u>

The XNR2000 employs an outer uncooled pressure vessel which surrounds the radial reflector and a regeneratively cooled inner pressure vessel which surrounds the reactor. The pressure vessel material considered is Inconnel INCO 718. Because the inner pressure vessel is subjected to a collapsing pressure of approximately 800 psi, longitudinal radial support ribs would be employed to transmit this load to the outer vessel. The radial support ribs would serve to separate and house the annular reflector segments. The two pressure vessels are capped at the top of the reactor by hemispherical heads. Hydrogen exits the reflector region and flows between the primary and secondary heads to cool the primary head covering the inner pressure vessel and provide additional heat input to the turbine.

XNR2000 BASELINE DESIGN EXCEEDS NASA REQUIREMENTS

	Baseline
Thrust (lb)	25,000
Isp (sec)	900
T/W	5.3
Reactor power (Mw)	510
Power density (Mw/L)	9.4
Max fuel temp (K)	2,880
Chamber temp (K)	2,669
Chamber pressure (psia)	766
Total flow (lb/sec)	27.8
Pump tip speed (ft/sec)	1,460
Turbine inlet temp (K)	227
Nozzle area ratio	200
Nozzle exit dia (ft)	5.8
Max engine length (ft)	15.3
Stowed engine length (ft)	11.0
No. of inner fuel elements	61
No. of outer fuel elements	90
Throttling at design Isp (%)	10

PRATT & WHITNEY XNR2000 CERMET NTRE

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<u>XNR2000 Baseline Design Exceeds NASA Requirements</u>

The table displays the cycle performance information of the baseline XNR2000. The baseline XNR2000 delivers 25,000 lb. of thrust at a specific impulse of 900 sec. with a thrust to weight ratio of 5.3. This power balance information was generated using the Marshall Space Flight Center/P&W Rocket Engine Transient Simulation (ROCKETS) System

XNR2000 ENGINE PERFORMANCE

Thrust = 25,000 lbf
T/W = 5.3
Isp = 900.0 sec

PROPELLANT FLOW ENGINE STATION CONDITIONS

Station Location	Pressure (psia)	Temperature (Deg K)	Flow (lbm/s)	Enthalpy (Btu/lbm)	Density (lbm/ft**3)
Engine Inlet	26.7	20.6	14.0	-108.0	4.38
Pump Inlet	25.7	20.6	14.0	-108.0	4.38
Pump Exit	2179.3	34.7	14.0	13.0	4.56
Nozzle Coolant Inlet	2157.6	34.8	8.4	13.0	4.55
Reflector Coolant Inlet	1932.6	103.1	28.1	440.9	1.77
Turbine Inlet	1901.6	226.9	11.8	1343.7	0.80
Turbine Exit	1218.2	207.2	11.8	1199.9	0.58
Outer Core Inlet	1108.9	210.4	27.8	1221.6	0.52
Inner Core Inlet	956.3	1659.4	27.8	8865.0	0.06
Chamber	765.9	2668.7	27.8	18188.3	0.03

REACTOR CHARACTERISTICS

Two-Pass Design		
Inner Core Diameter	11.5	in
Outer Core Diameter	18.1	in
Reflector Diameter	32.2	in
Pressure Drop	344.1	psia
Max. RX Fuel Temp.	2880.0	K
Outer Core Fuel Mt'l	Mo-UO2,90	
Inner Core Fuel Mt'l	W-UO2,61	
Power Density	9.41	MW/l
Total Power	510.4	MW

NOZZLE CHARACTERISTICS

Nozzle Area Ratio	200.	
Throat Area	18.8	in**2
Exit Dia.	5.8	ft
Nozzle C*	16443	ft/s
Nozzle Length	10.6	ft
Total S.A.	22524	in**2
Regen. Construction	Cu Tubes	
Rad. Construction	Cb Sheet	

PUMP CHARACTERISTICS

Overall Efficiency	73.2	%
Head Rise	69,018	ft
NPSH Avail.	302.9	ft
Speed	71,323	RPM
Power	2403.2	HP
Vol. Flow Rate	1379	gpm
Stg I Flow Coeff.	0.114	-
Stg II Flow Coeff.	0.113	-
Stg I Head Coeff.	0.521	-
Stg II Head Coeff.	0.521	-
Utip 1	1460.	ft/s
Utip 2	1460.	ft/s

TURBINE CHARACTERISTICS

Inlet Temperature	226.9	K
Inlet Pressure	1901.6	psia
Mass Flow	11.8	lbm/s
Overall Efficiency	85.4	%
Speed	71,233	RPM
Pressure Ratio	1.56	-
Inlet Flow Parameter	0.125	-
Overall Velocity Ratio	0.54	-
DH Actual	143.8	Btu/lb
AN**2(E-08)	193.	
Mean Dia.	4.66	in

OPERATION AT 2500K CAN BE ACCOMODATED WITHIN BASELINE CONFIGURATION

	Baseline	
Thrust (lb)	25,000	25,000
Isp (sec)	900	865
T/W	5.3	5.3
Reactor power (Mw)	510	492
Power density (Mw/L)	9.4	9.1
Max fuel temp (K)	2,880	2,740
Chamber temp (K)	2,669	2,500
Chamber pressure (psia)	766	758
Total flow (lb/sec)	27.8	28.9
Pump tip speed (ft/sec)	1,460	1,482
Turbine inlet temp (K)	227	216
Nozzle area ratio	200	200
Nozzle exit dia (ft)	5.8	5.8
Max engine length (ft)	15.3	15.3
Stowed engine length (ft)	11.0	11.0
No. of inner fuel elements	61	61
No. of outer fuel elements	90	90
Throttling at design Isp (%)	10	10

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<u>Operation at 2500k Can Be Accommodated Within Baseline Configuration</u>

The baseline cycle information is displayed and compared to the XNR2000 engine operating at a chamber temperature of 2500K. The power balance for both cycle points was generated by requiring the reactor exit Mach numbers to equal 0.3 and deliver 25,000 lb. of thrust.

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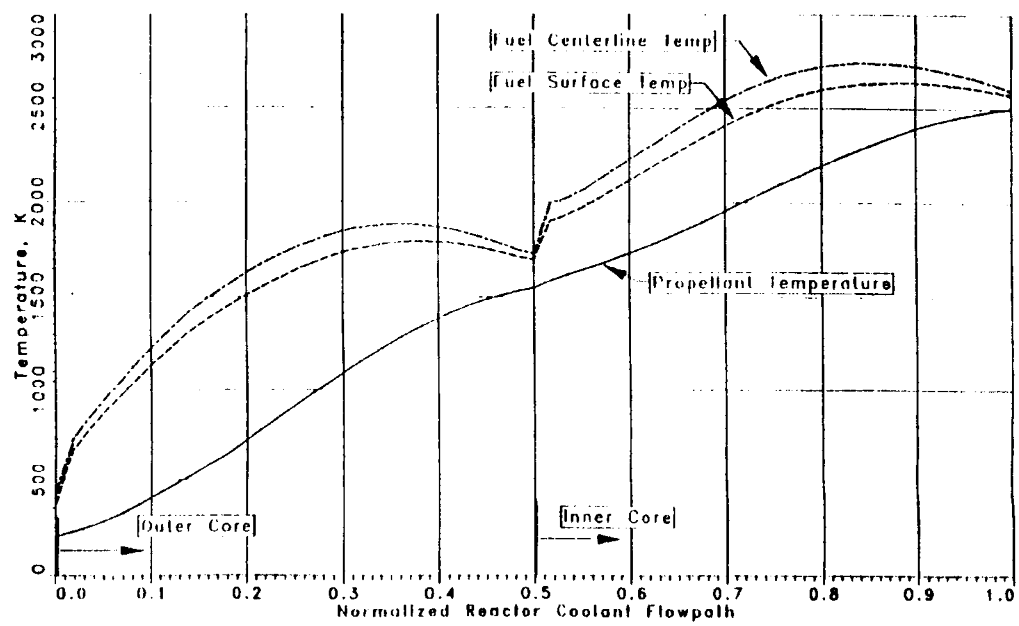
PEAK FUEL TEMPERATURE DROPS TO 2740K FOR 2500K PROPELLANT DELIVERY



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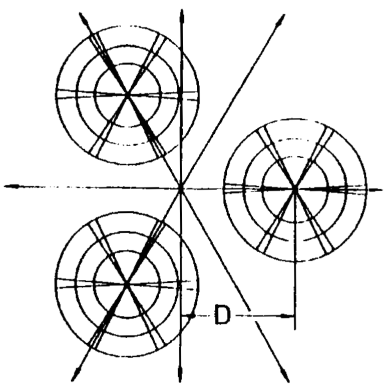
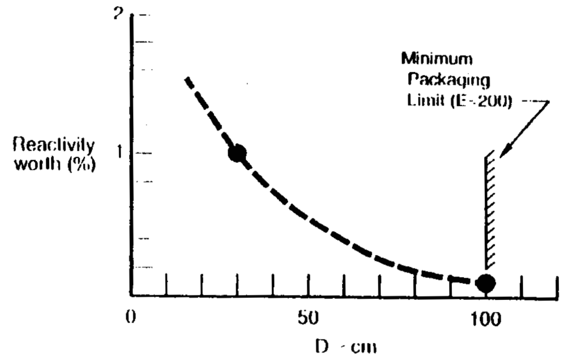
PRELIMINARY ENGINE CLUSTERING STUDY INDICATES LIMITED NEUTRONIC INTERACTION



Three engine clustering arrangement



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__Preliminary Engine Clustering Study Indicates Limited Neutronic Interaction__

A conservative engine clustering model was developed and the K_{eff} was evaluated for a cluster of three XNR2000 baseline engines as a function of separation distance. The separation distance is defined as shown in the figure. As displayed in the chart, core neutronic coupling was found to have no effect in clustering engines for distances required to account for nozzle skirts.

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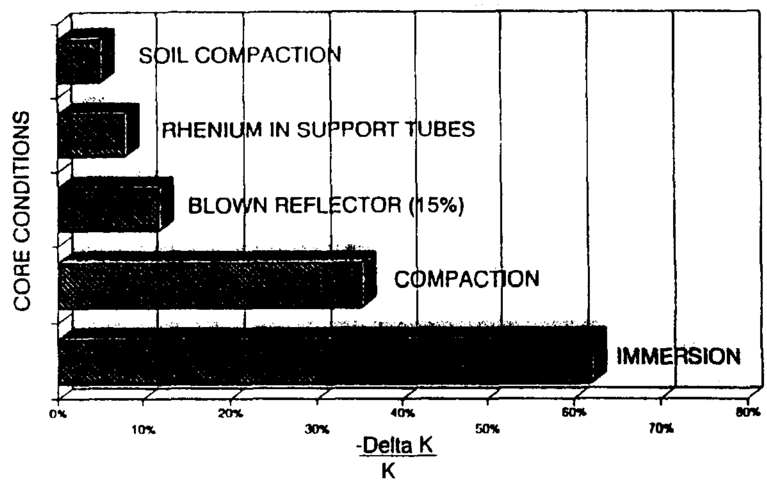
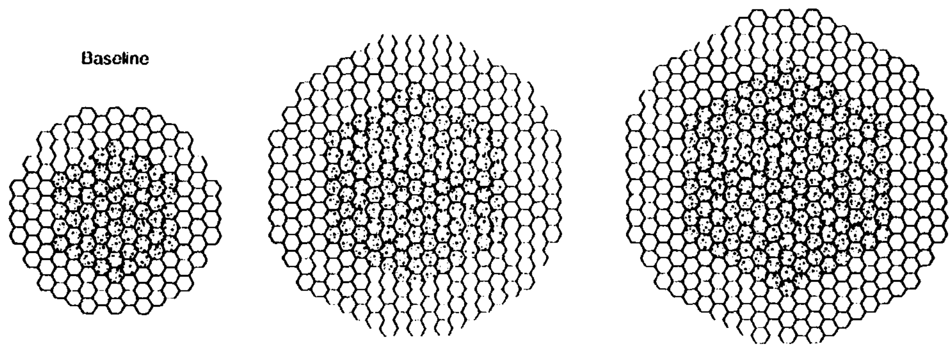
REENTRY & WORST CASE ACCIDENT SCENARIO CRITICALITY ANALYSIS



Reentry & Worst Case Accident Scenario Criticality Analysis

A 16-group diffusion code (VENTURE/COMBINE) analysis was conducted to determine worst case accident scenario criticality. The negative reactivity insertion is shown for several accident scenario core conditions. The XNR2000 would go subcritical for all accident conditions evaluated. The largest negative reactivity insertion occurred for water immersion. The impact of rhenium rods in tubes surrounding the outer core elements was also evaluated and found to provide adequate negative reactivity insertion to be used as a potential back-up safety mechanism. The blown reflector analysis was conducted assuming that 15% of the total reflector was removed from the system.

DESIGN ALLOWS THRUST FLEXIBILITY WITH COMMON FUEL ELEMENTS



25,000 lbf thrust	50,000 lbf thrust	75,000 lbf thrust
total no. of fuel elements: 151	total no. of fuel elements: 313	total no. of fuel elements: 379

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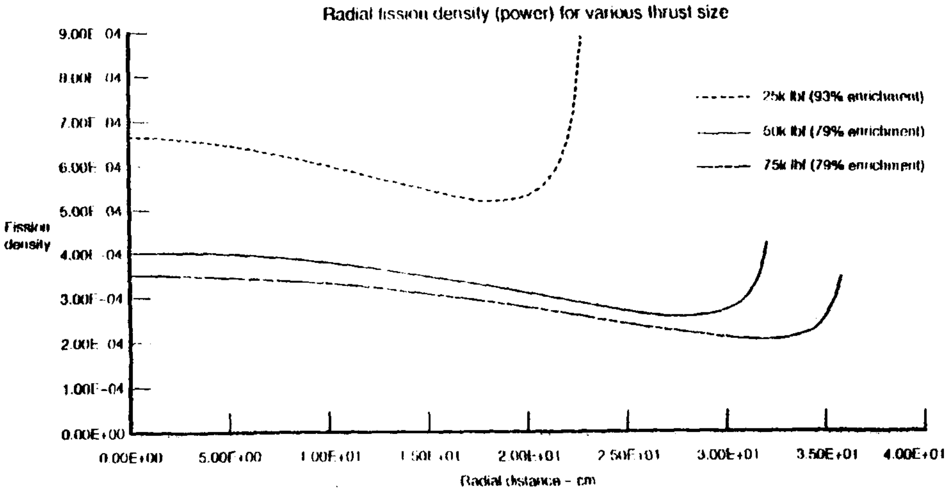
75398

<u>Design Allows Thrust Flexibility With Common Fuel Elements</u>

The XNR2000 was configured to provide thrust flexibility. The system can provide thrust ranging from approximately 20,000 lb to 90,000 using the same fuel element design, core configuration, and support methodology by simply varying the number of inner and outer core fuel elements.

REACTOR NEUTRONICS BEHAVIOR SIMILAR OVER THRUST RANGE



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<u>Reactor Neutronics Behavior Similar Over Thrust Range</u>

Radial power profiles for three XNR2000 core sizes are shown. The 50,000 lbf and 75,000 lbf can be made critical with 79% enriched fuel at the fuel-metal volume ratio of 60/40.

XNR2000 CYCLE PARAMETERS ARE SIMILAR FOR VARIOUS THRUST SIZES

	Baseline		
Thrust (lb)	25,000	50,000	75,000
Isp (sec)	900	901	897
T/W	5.3	6.6	7.9
Reactor power (Mw)	510	1,022	1,513
Power density (Mw/L)	9.4	9.1	11.1
Max fuel temp (K)	2,880	2,880	2,880
Chamber temp (K)	2,669	2,676	2,657
Chamber pressure (psia)	766	735	836
Total flow (lb/sec)	27.8	55.5	83.6
Pump tip speed (ft/sec)	1,460	1,527	1,738
Turbine inlet temp (K)	227	230	257
Nozzle area ratio	200	200	200
Nozzle exit dia (ft)	5.8	8.3	9.5
Max engine length (ft)	15.3	20.3	22.7
Stowed engine length (ft)	11.0	12.4	12.0
No. of inner fuel elements	61	127	169
No. of outer fuel elements	90	186	210
Throttling at design Isp (%)	10	TBD	TBD

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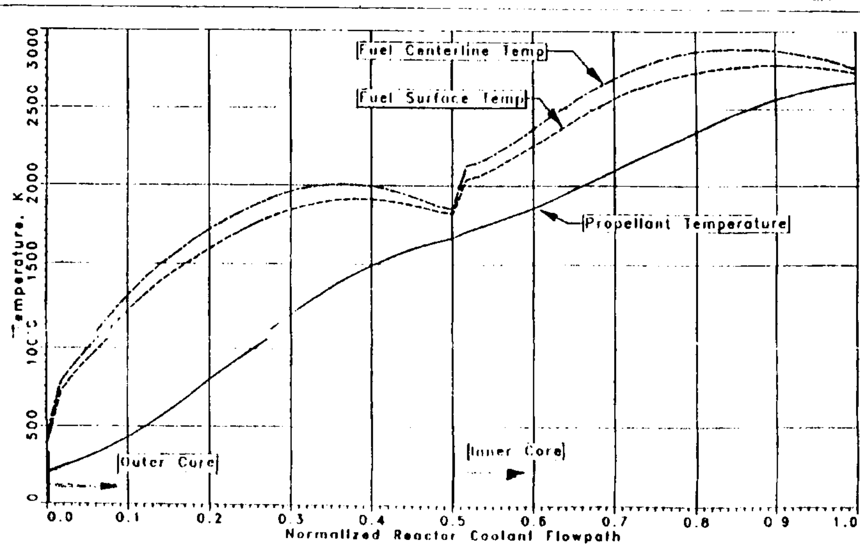
REACTOR THERMAL HYDRAULICS AT 50K ARE SIMILAR TO BASELINE



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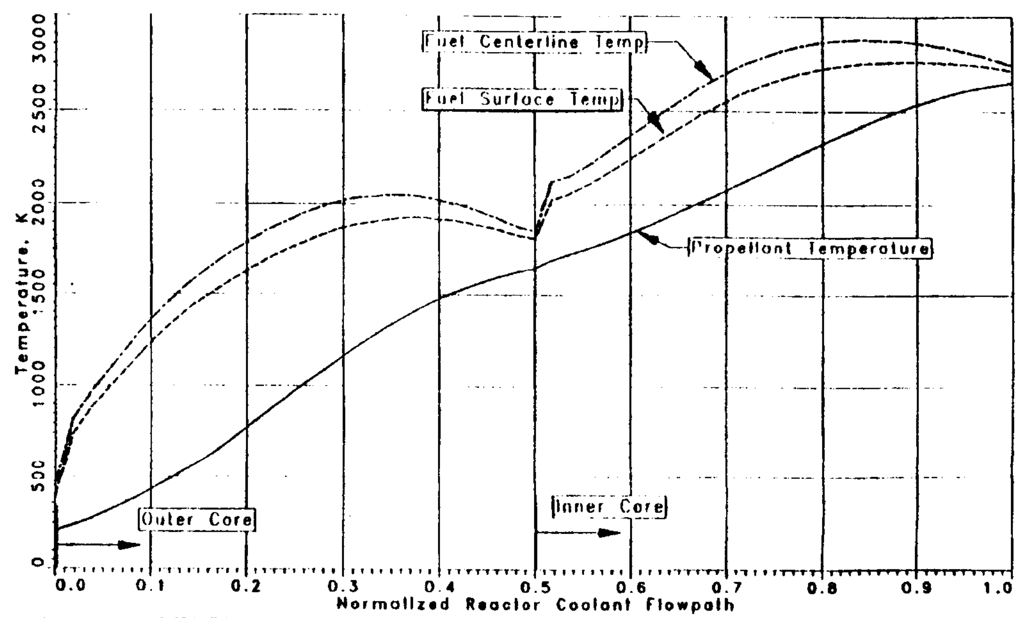
REACTOR THERMAL HYDRAULICS AT 75K THRUST ARE SIMILAR TO BASELINE



PRATT & WHITNEY XNR2000 CERMET NTRE

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CERMET ENGINE WEIGHT SUMMARY VS THRUST SIZE

Thrust level	25,000 lb	50,000 lb	75,000 lb
Inner core	940	1,662	2,212
Outer core	937	1,644	1,856
Support structure	115	250	425
Internal shield	250	300	310
Axial reflector	50	80	100
Radial reflector and control	500	800	1,000
Valves and controller	425	525	590
Pressure vessel	550	800	1,000
Upper core assembly	220	300	400
Nozzle skirt	250	500	750
Turbopump	75	125	175
Thrust structure	440	600	700
Total engine (lb)	4,752	7,586	9,518
T/W	5.26	6.59	7.88

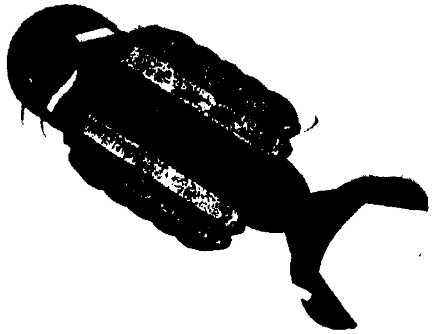
PRATT & WHITNEY XNR2000 CERMET NTRE

25400

<u>Cermet Engine Weight Summary vs. Thrust Size</u>

A Weight Summary of the XNR2000 for the thrust levels evaluated is shown. The thrust-to-weight ratios for the XNR2000 are high relative to other conventional NTRE's. Several features contribute to the high thrust to weight of the XNR2000. The XNR2000 can operate at a high power density because of the high conductivity of the Cermet fuel and the thermal fluid mixing in the upper plenum. The fast spectrum provides a compact core with no moderator material and the high strength refractory metal fuel elements allow a lightweight support structure. The use of refractory methods and the compact core design reduces required shielding weight. Additionally, the separation of the reactor into two regions allows the use of a lightweight Molybdenum based matrix in the outer core. These features of the XNR2000 NTRE contribute to the high thrust-to-weight.

CERMET APPROACH PROVIDES HIGH PERFORMANCE AND LOW RISK



Thrust = 25,000 lb	Thrust = 50,000 lb	Thrust = 75,000 lb
Isp = 900 sec	Isp = 901 sec	Isp = 897 sec
T/W = 5.3	T/W = 6.6	T/W = 7.9
Dia_{Max} = 5.8 ft	Dia_{Max} = 8.3 ft	Dia_{Max} = 9.5 ft
Stowed length = 11.0 ft	Stowed length = 12.4 ft	Stowed length = 12.0 ft
Deployed length = 15.3 ft	Deployed length = 20.3 ft	Deployed length = 22.7 ft

PRATT & WHITNEY XNR2000 CERMET NTRE 25409

Cermet Approach Provides High Performance and Low Risk

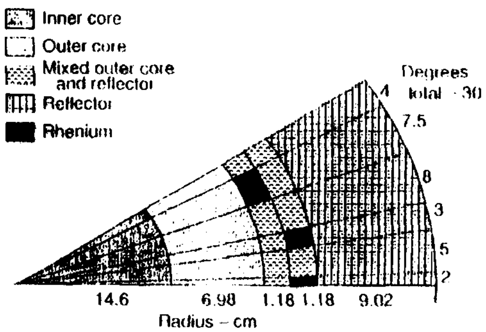
A conceptual NTRE, the XNR2000, has been presented that is powered by a fast spectrum, cermet fueled reactor core. The baseline XNR2000 system delivers 25,000 lbf of thrust at a specific impulse of 900 seconds and thrust to weight of 5.3. The distinguishing features of this system are the dual pass reactor configuration and fast spectrum, cermet fueled reactor. These features have been incorporated into the design, as well as knowledge gained from the ROVER/NERVA, GE710 and ANL programs, to develop a safe and robust Nuclear Thermal Rocket Engine for manned space exploration missions.

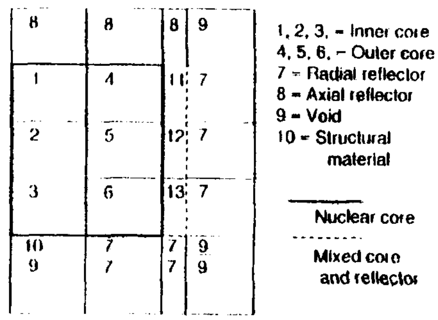
XNR2000 NEUTRONICS ARE BENCHMARKED AND CONFIRMED

- Design analysis methodology
- Benchmark analysis and criticality summary
- Power profiles
- Reactivity and control system
- Neutron and gamma–ray fluence
- Inherent safety features

PRATT & WHITNEY XNR2000 CERMET NTRE 26492

MODELS DEVELOPED TO ACCURATELY PREDICT REACTOR NEUTRONICS





PRATT & WHITNEY XNR2000 CERMET NTRF

25493

Models Developed To Accurately Predict Reactor Neutronics

A three dimensional model of XNR2000 core is developed. Thirty radial and azimuthal regions and 6 axial zones are used to model the details of the inner core, the outer core, the interfacial core reflector and the lateral support structure are included in the model. Six axial zones are used to address the axial temperature gradient in the inner and the outer cores. Group average neutron cross-sections for all 180 regions are generated at their average operating temperatures. Each region is divided to tens of finite volumes for the calculation of flux and effective multiplication factor.

DESIGN ANALYSIS METHODOLOGY TAILORED TO FAST SPECTRUM

- Multigroup cross–sections generated by COMBINE (ENDFB–V)
- MCNP (4.2) used for complex geometries
- BOLD VENTURE (3–D diffusion) used for power profile and reactivity
- ANISN (I–D ,Sn) used for analysis of hetrogeneous boundaries
- Results benchmarked with GE 710 testing
- Results independently confirmed by B&W and ANL

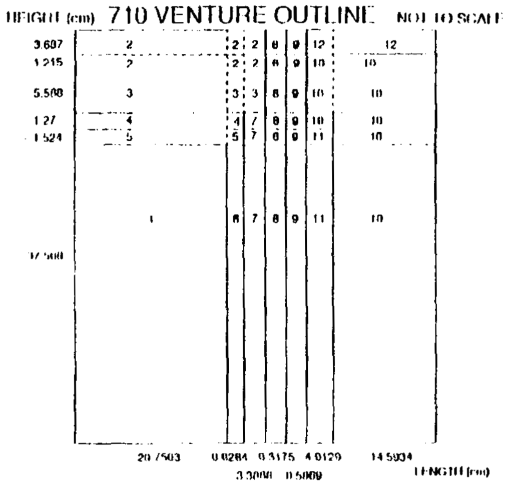
PRATT & WHITNEY XNR2000 CERMET NTRF 25494

<u>Design Analysis Methodology Tailored To Fast Spectrum</u>

The major neutronic design analysis tools used for core physics studies include:

> **COMBINE:** A multigroup neutron cross-section generation code which combines the PHROG fast neutron library with the INCITE thermal neutron library (available through RSIC).
>
> **BOLD VENTURE:** A 3-D neutron diffusion code (available through RSIC).
>
> **ANISN:** A 1-D transport (Sn) code (available through RSIC).
>
> **MCNP:** A Monte Carlo code for stochastic analysis of the core criticality, power distribution and neutron and gamma-ray doses (available through LANL and RSIC).

VENTURE MODEL GENERATED FOR GE 710 MOCKUP 1A BENCHMARK



Material list

1 Core U, W, Ta, Al, O
2 Tube Sheet 303 SS
3 Tube Sheet and Mo 303 SS, Mo
4 Mo Transition Mo
5 Mo Plug Mo, Ta, W
6 Cladding Ta, W
7 Be (.85), Al
8 Shell 303 SS
9 Transition Al
10 Inner Reflector Zone Be (.85), Al
11 Outer Reflector Zone Be (.90), Al
12 Gap

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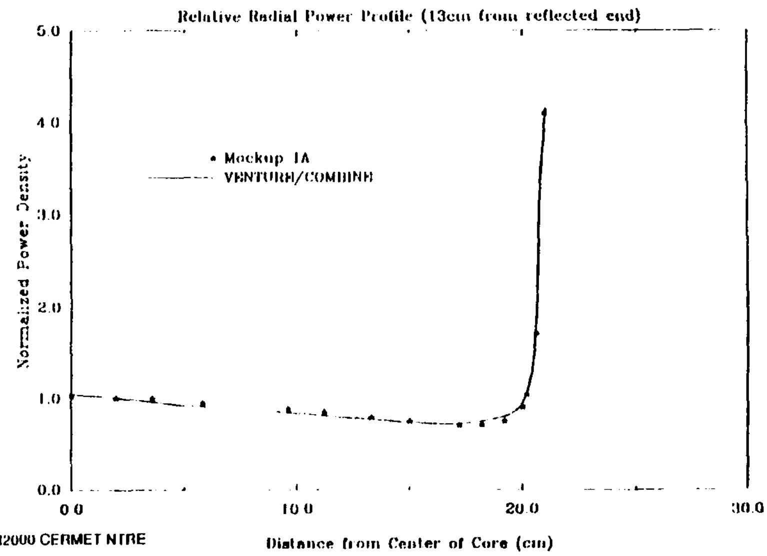
<u>Venture Model Generated For GE710 Mockup 1A Benchwork</u>

GE710 program Mockup 1A critical configuration was used to benchwork the 3-D, 16-group COMBINE/VENTURE and continuous energy MCNP 4.2 models. Mockup 1A features core physics characteristics comparable with 25000 lbf XNR2000 engine design. The materials concentration and core dimensions are taken directly from the GEMP 442 report.

OUTSTANDING PREDICTION ACCURACY IS HARD TO BELIEVE



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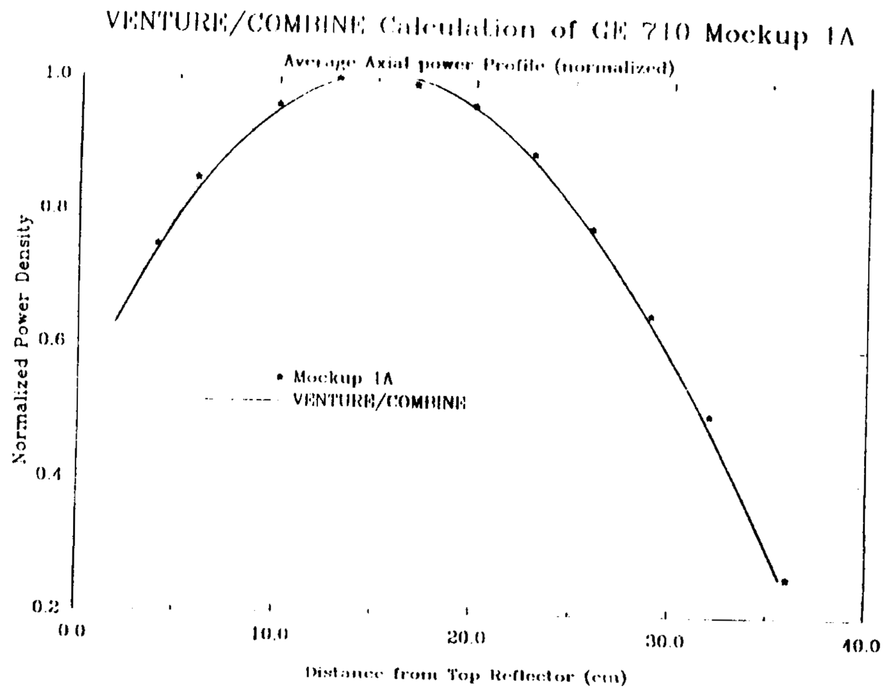
Outstanding Prediction Accuracy

VENTURE/COMBINE calculated values of the normalized radial power profile compares well with the GE710 experimental results. Both experimental and calculated power profiles are normalized to the power level at the radial distance of 2 cm from the core centerline. The calculated values of the radial power density beyond the last measurement point are not shown. The measured value of the relative power density is 4.1 where the COMBINE/VENTURE calculated maximum radial power density is 8.3. The maximum power density close to the reflector is very sensitive to the position.



<u>VENTURE/COMBINE Calculation of GE710 Mockup 1A</u>

COMBINE/VENTURE calculated values of the average axial power profile compares well with GE710 Mockup 1A experimental results. Two experimental points at the top and bottom of the reactor are excluded. Large uncertainty in experimental data at the unreflected end of the Mockup 1A reactor. Additionally, the VENTURE/COMBINE calculated value of K_{eff}, 0.991, compares well with the measured value of 1.000.

XNR2000 BASELINE CORE CRITICALLITY INDEPENDANTLY CONFIRMED

	Venture/Combine (P&W)	MCNP (P&W)	MCNP (B&W)	MCNP (ANL)
Keff	1.0183 (24 groups)	1.021	1.025	1.007
	1.0183 (16 groups)			
	1.0210 (12 groups)			
	1.0601 (8 groups)			
	1.0559 (4 groups)			

- Good agreement between 2–D, 16 groups diffusion calculation and MCNP
- Good agreement between independently performed MCNP calculations

PRATT & WHITNEY XNR2000 CERMET NTRE

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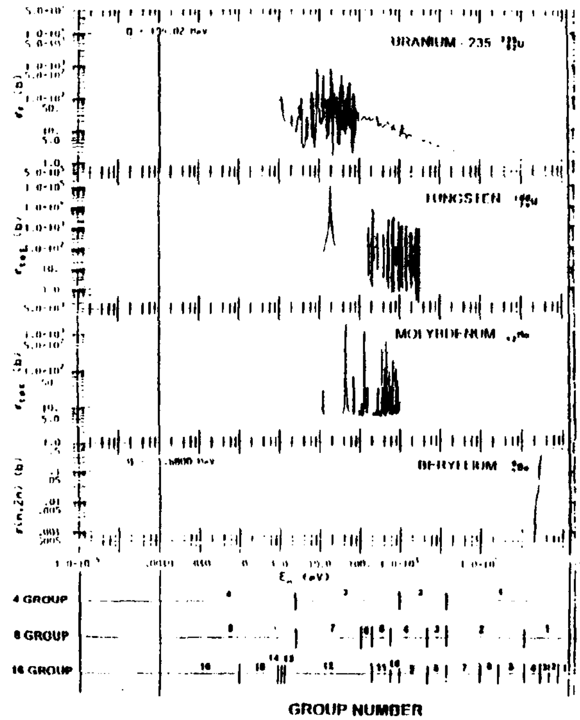
XNR2000 Baseline Core Criticality Independently Confirmed

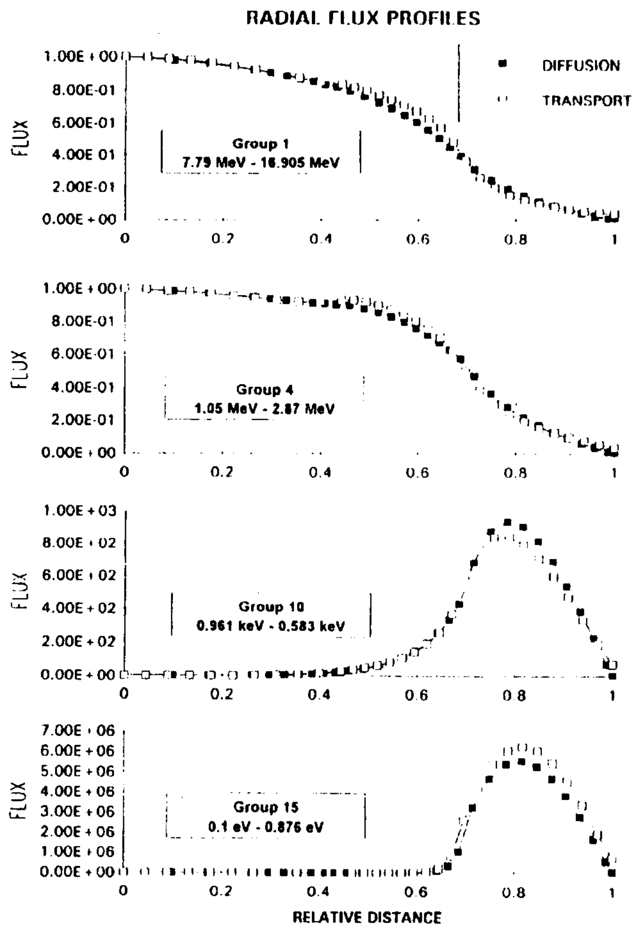
The 16 group COMBINE/VENTURE K_{eff} calculation of the XNR2000 core shows good agreement with MCNP calculated values of K_{eff}. Pratt & Whitney MCNP calculations are for a minimum of 500,000 histories. Babcock and Wilcox and Argonne National Laboratory calculations of XNR2000 core K_{eff} are based on a minimum of 100,000 histories. The small differences between MCNP calculated results are due to slightly different number densities and cross-section libraries used.

16 GROUP ACCURATELY MODELS SPECTRUM



<u>16 Group Accurately Models Spectrum</u>

The selection of neutron energy groups is influenced by the location of isolated and non-isolated resonances of uranium, tungsten, molybdenum, and the energy threshold for the Be (n,2n) reaction. With a carefully selected energy partition, 12 group calculation proved to be adequate. The optimum choice of energy partition for 16 group calculation is shown and was used in all reactor studies.



<u>XNR2000 Radial Flux Profiles</u>

Radial flux profiles for the XNR2000 baseline core as presented. Both transport and diffusion theory are used to calculate total neutron flux for energy groups 1, 4, 10 and 16. The difference in the calculated value of flux at the vicinity of the reflector-core boundary is due to the fix law approximation used in the diffusion theory. There is also a noticeable difference between predicted values of flux for intermediate and low energy neutron groups in the reflector

CONSTANT ENRICHMENT
3-D POWER PROFILE AT CRITICALITY

Reactor location	Normalized peak power
Top	.72
	.96
Middle	1.0
	.82
Bottom	.36

Reflector raised 1.016 cm

Keff = 1.000

PRATT & WHITNEY XNR2000 CERMET NTR

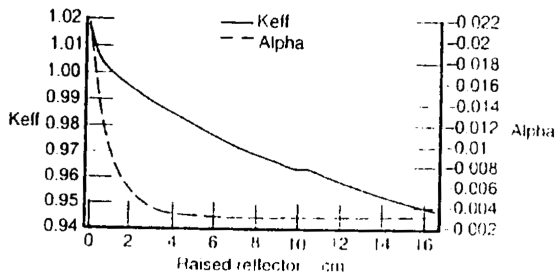
25498

Constant Enrichment 3-D Power Profile At Criticality

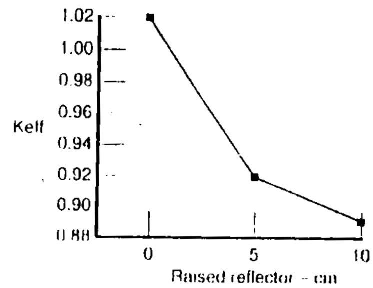
Radial power profile at different axial location of XNR2000 core. Ten degree reflector segments are raised for 1.016 cm to achieve K_{eff} = 1.0. Circumferential power tilt at the axial location of 50 cm is due to the raised reflectors.

HIGH REFLECTOR WORTH ENABLES ROBUST BASELINE CONTROL APPROACH

Reflector worth calculations



Shutdown calculations



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25501

<u>High Reflector Worth Enables Robust Baseline Control Approach</u>

The 25000 lbf XNR2000 baseline engine is powered by a compact fast reactor. The neutron leakage from the core region to the reflector is very significant. One of the options to control the reactor is the axial movement of the 10° reflector segments. Large reflector segments (50°) can be used for large insertion of negative reactivity and reactor shutdown. The reflector worth calculations were conducted as a function of distance raised for a bank of six 10° reflector segments. The shutdown calculations were conducted for six 50° reflector segments.

REACTOR DESIGN PROVIDES ROBUST REACTIVITY AND CONTROL MARGIN

Reactivity effect	Reactivity% $\frac{\Delta k}{k}$
Temperature effect (30% 3000k)	−.6 ±.3
Fuel burnup (6000 mw–hr)	−.1 ±.03
Required excess Reactivity (maximum)	+1.0
Design excess reactivity	2.0 ± 0.5

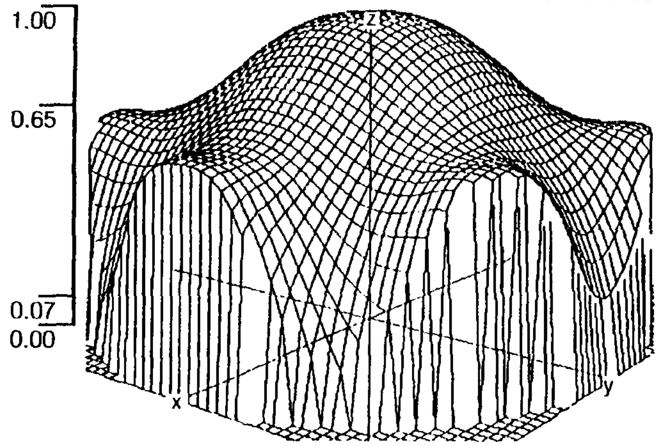
Control system requirements	
Installed reactivity (maximum)	2.5
Minimum scram requirements	2.5
Minimum required control system worth	5.0
Design control system worth	10.0

PRATT & WHITNEY XNR2000 CERMET NTRE 25500

Reactor Design Provides Robust Reactivity and Control Margin

COMBINE BOLD VENTURE computer code system is used to calculate the reactivity effect due to operational temperature and fuel burnup. High temperature cross-sections are generated and used to estimate the reactivity temperature effect at full power operational temperature. A total of 12 hours of full power operation is assumed to calculate the fuel burnup reactivity worth at the end of core life. The reactivity installed in the core is in excess of 2% which is needed to compensate for the loss of reactivity as the operation proceeds. The design control system worth is about -10%.

CONSTANT ENRICHMENT 3-D POWER PROFILE WITH RAISED REFLECTORS



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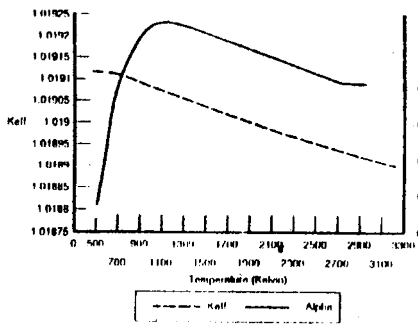
25502

<u>Constant Enrichment 3-D Power Profile With Revised Reflector</u>

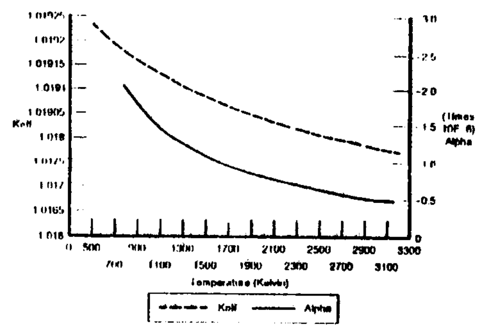
Power tilt due to the axial displacement of ten degree reflector segments is shown. The 10 degree reflector segments are raised by 5cm. The COMBINE BOLD VENTURE computer code system is used to calculate 3-D power distribution in the mid-core region. The power peaking at the core central axis is increased due to the significant leakage loss of neutrons through the opening in the radial reflector.

REACTOR HAS DESIRABLE NEGATIVE TEMPERATURE COEFFICIENT

Inner Core



Outer Core



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25503

Reflector Has Desirable Negative Temperature Coefficient

- Temperature coefficient of reactivity is very small.
- Inner core fuel temperature coefficient is one order of magnitude smaller than the outer core fuel temperature coefficient.
- Outer core fuel temperature is comparable with GE710 Mockup 1A fuel temperature coefficient.

XNR2000

Inner Core: α @ 2200k) = -8.0×10^{-8} $\Delta K/K$ / °K

Outer Core: α @ 2200k) = -6.8×10^{-7} $\Delta K/K$ / °K

ADEQUATE INTERNAL SHIELDING INCLUDED IN DESIGN

Neutrons	XNR2000	NASA limits
Fast neutron flux (E>1.0 mev)	$(8.0 \pm 2.0) \times 10^{10}$	2.0×10^{12}
Intermediate energy neutron flux	$(2.4 \pm .6) \times 10^{12}$	3.0×10^{12}
Thermal neutron flux	$(3.6 \pm .9) \times 10^{11}$	6.0×10^{11}

Gamma – rays

Model results indicate gamma–ray fluence is very sensitive to system geometry. A refined estimation of gamma – ray fluence will require further definition of configuration and constraints

PRATT & WHITNEY XNR2000 CERMET NTRE 25805

Adequate Internal Shielding Included In Design

MCNP is due to calculate the fast, intermediate and thermal neutron fluxes at the upper part of the core. Fast and thermal neutron fluxes are significantly lower than the limits specified for the baseline design. Accurate estimation of the gamma-ray flux at the upper part of the shielded core require more detailed information on the upper core structural materials.

SUMMARY OF XNR2000 REACTOR NUCLEAR DESIGN

- State of the art analysis techniques employed to ensure design criticality, controllability and safety

- High confidence provided by benchmark analysis and independent evaluations by B&W and ANL

- Evaluation of all major reactor issues confirm advantages and flexibility of baseline approach

PRATT & WHITNEY XNR2000 CERMET NTRE

25507